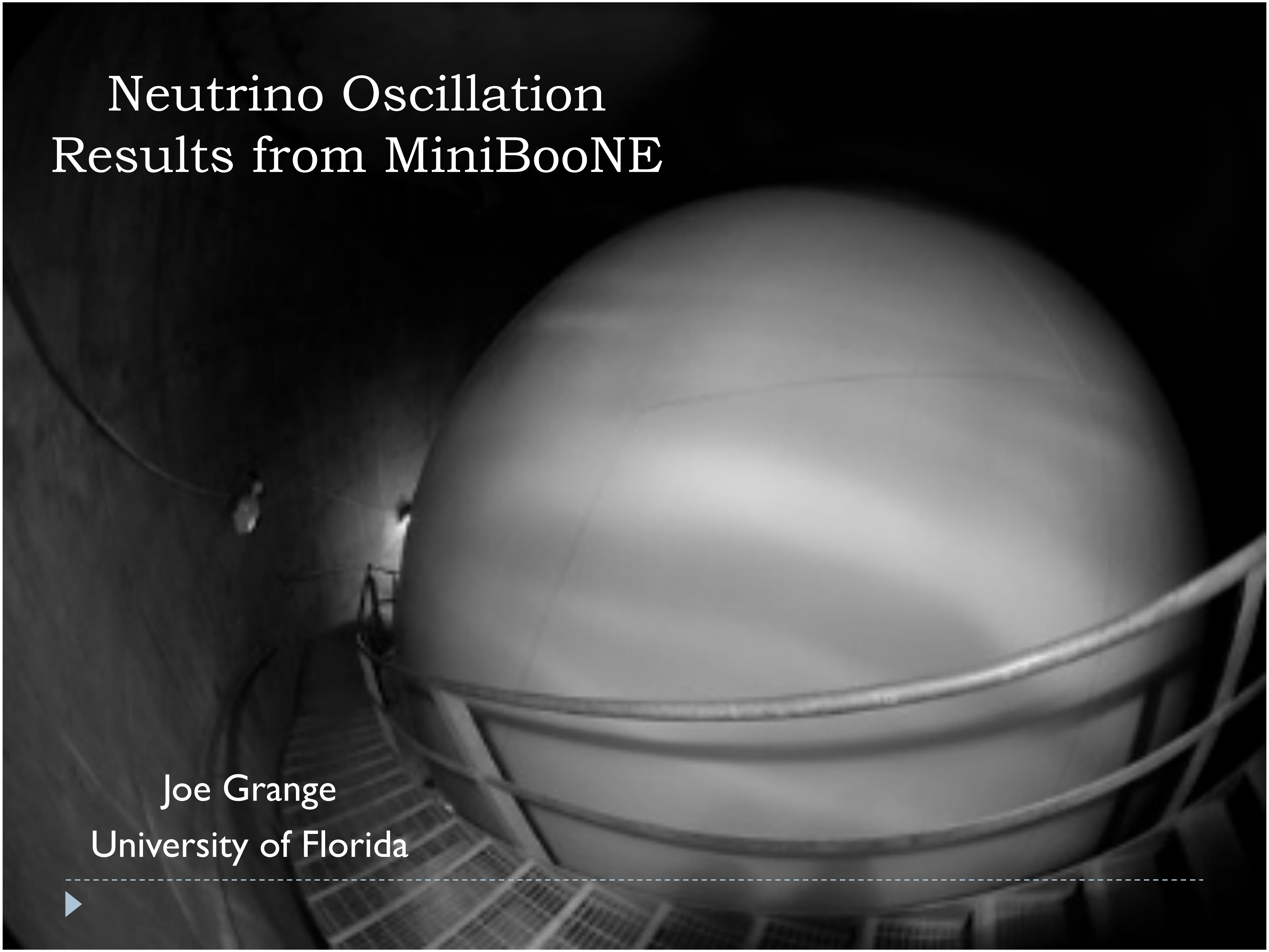
Neutrino Oscillation Results from MiniBooNE



Joe Grange
University of Florida

Outline

- MiniBooNE motivation
- The experiment
- Oscillations
    - Analysis
    - Results
- Summary and outlook

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ν Oscillations

- Neutrinos oscillate! One of the few concrete BSM results. Implications:
  - oscillation shape strongly supports massive ν's
  - ν Hamiltonian eigenstates are NOT flavor eigenstates
  - Lepton flavor is not conserved ($\nu_e \rightarrow \nu_\mu$, $\nu_\mu \rightarrow \nu_\tau$, $\nu_e \rightarrow \nu_\tau$)

- Embarrassingly brief formalism: ν born of type α propagates according to

$$\psi(x) = \Sigma_k U_{\alpha k} \times e^{ip_k x - iE_k t}$$

PMNS mixing matrix - describes mixing between ν flavor state α, mass state *k*

- Under the approximations of only two ν masses and

$$t \approx x \qquad p_k \approx E - \frac{m_k^2}{2E}$$

after travelling a distance L the ν born as α has survival probability (detected as α) of

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

and an oscillation probability of

$$P(\underset{\alpha \neq \beta}{\nu_\alpha \rightarrow} \nu_\beta) = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

ν Oscillations

"Disappearance"

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

"Appearance"

$$P(\underset{\alpha \neq \beta}{\nu_\alpha \rightarrow \nu_\beta}) = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Physics: θ osc. amplitude; Δm^2 osc. frequency

ν Oscillations

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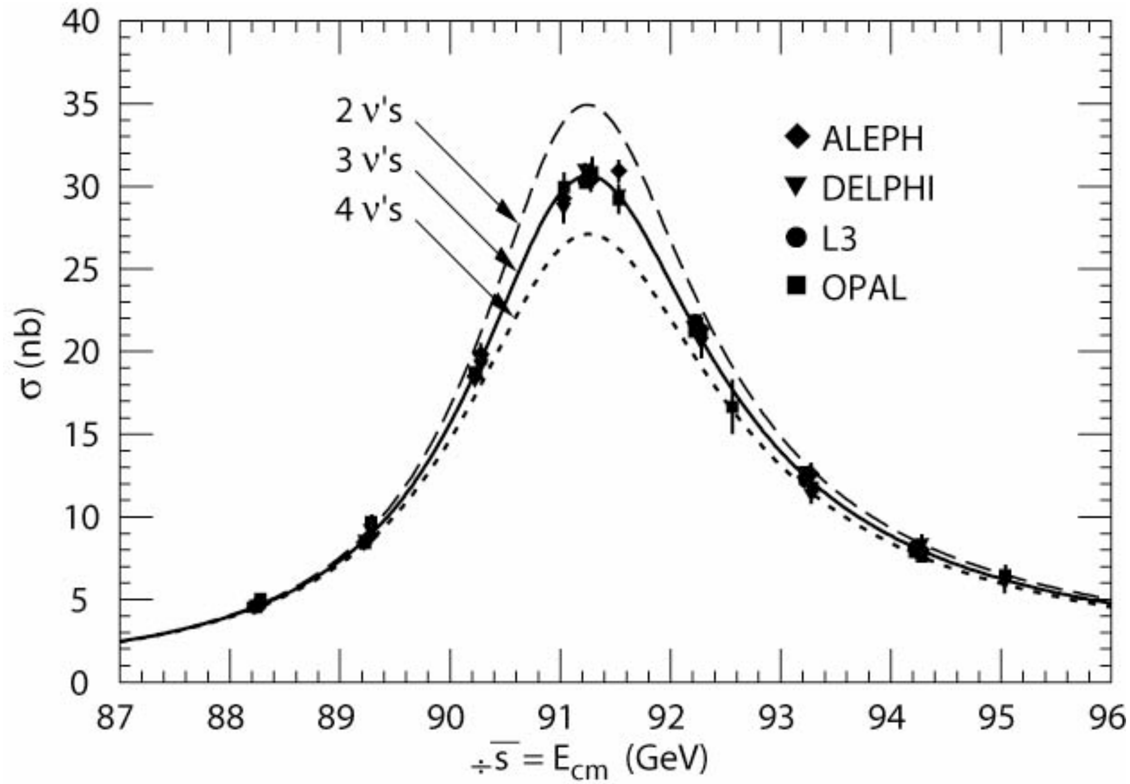
Physics: θ osc. amplitude; Δm^2 osc. frequency

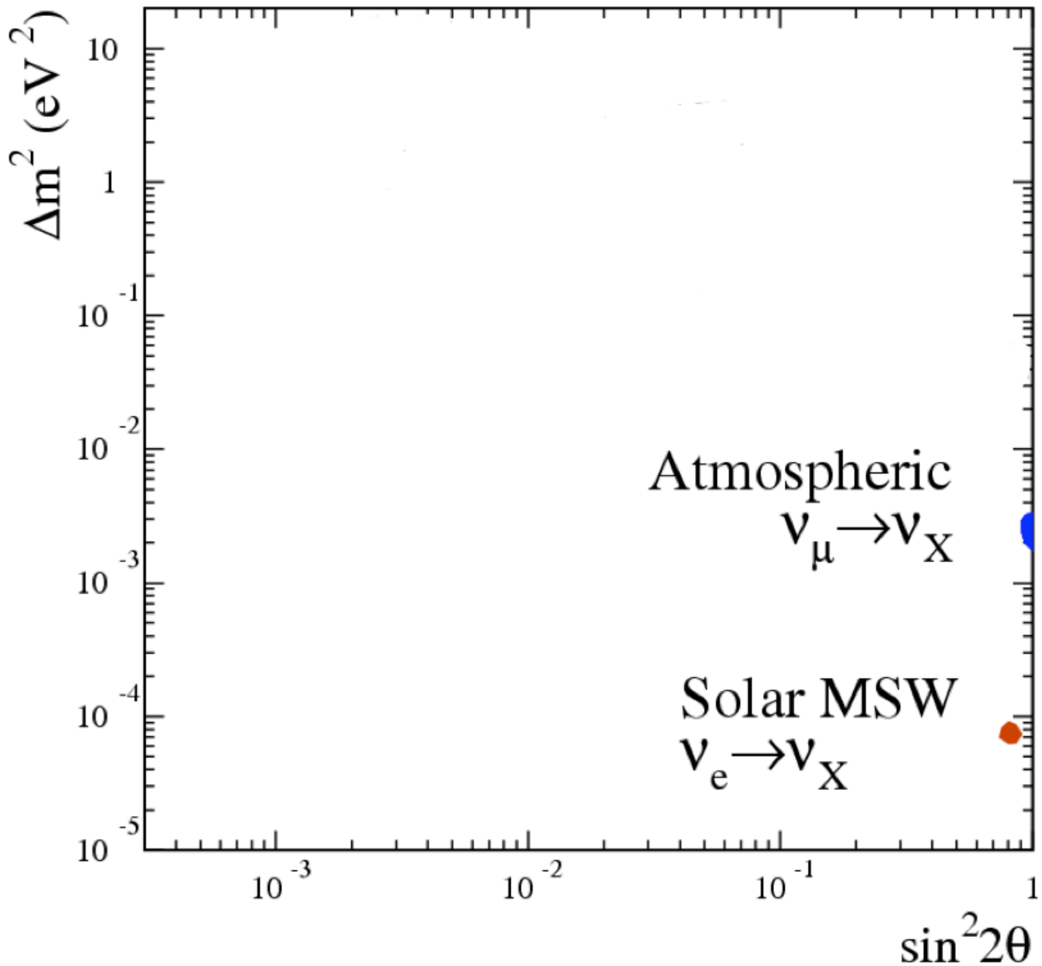
Experiment: E ν energy, L distance from ν creation to detector

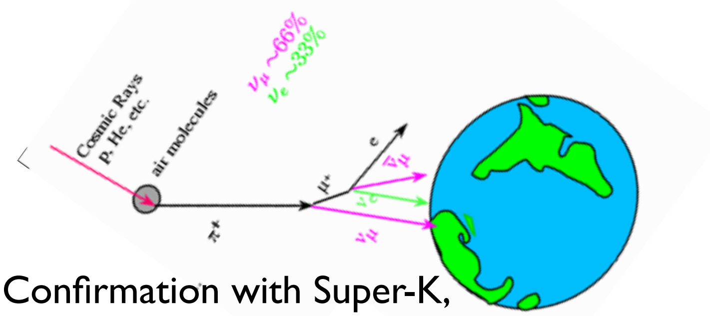
- Large Electron-Positron collider data: exactly 3 active, light ν flavors



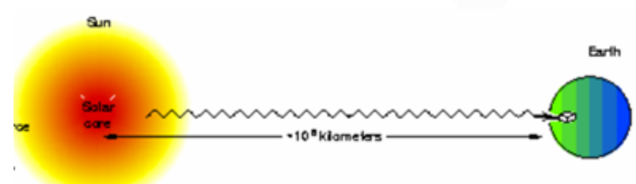
- We also know of 3 ν's: ν_e, ν_μ, ν_τ
- 3 ν's require two independent sets of Δm^2 mixing

This is observed and confirmed!



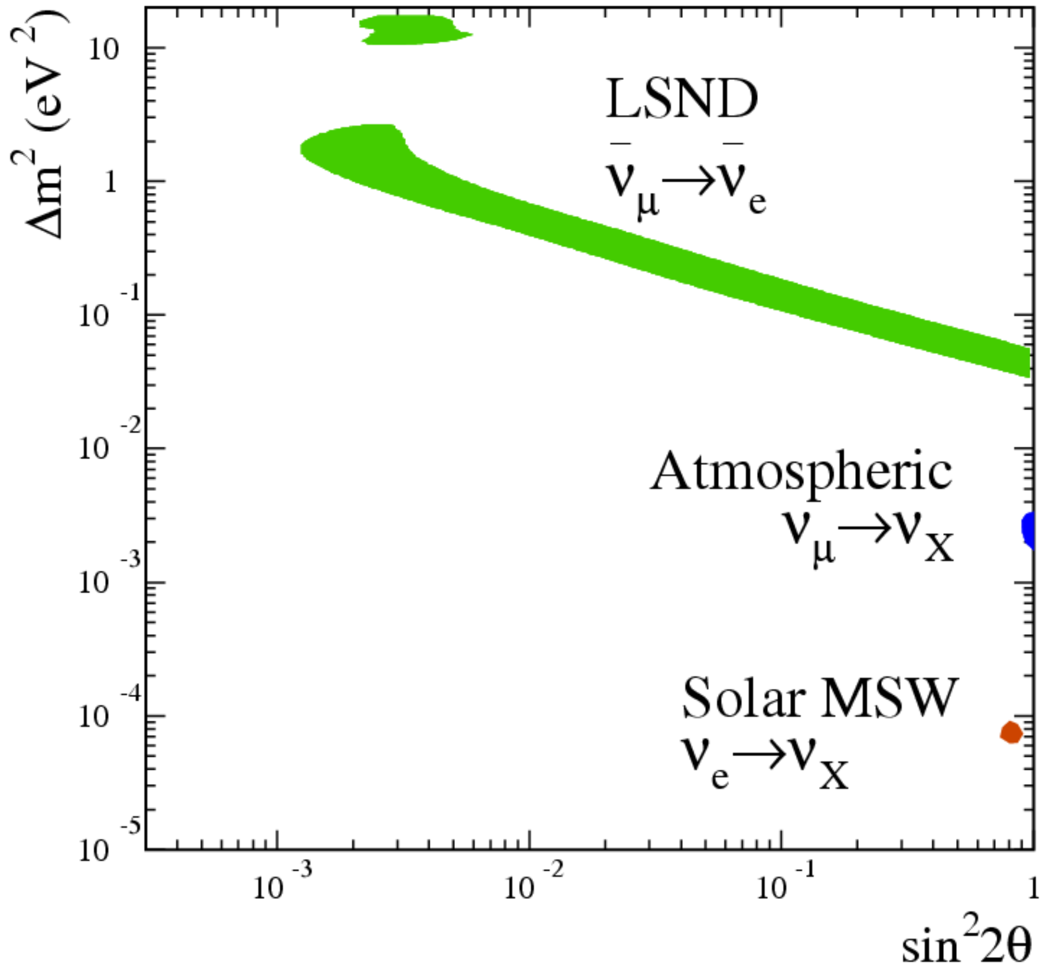


Confirmation with Super-K, K2K and MINOS data



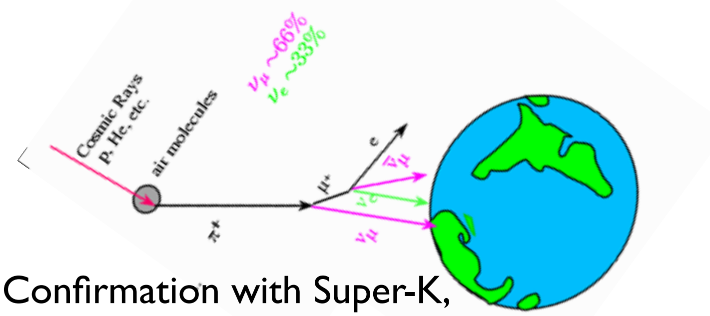
Confirmation with SNO, Kamland data

However…

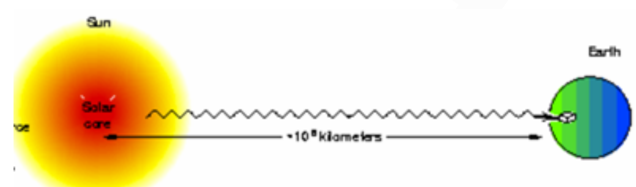


Evidence for high Δm^2 mixing from LSND experiment

some hints from cosmology and reactor data as well

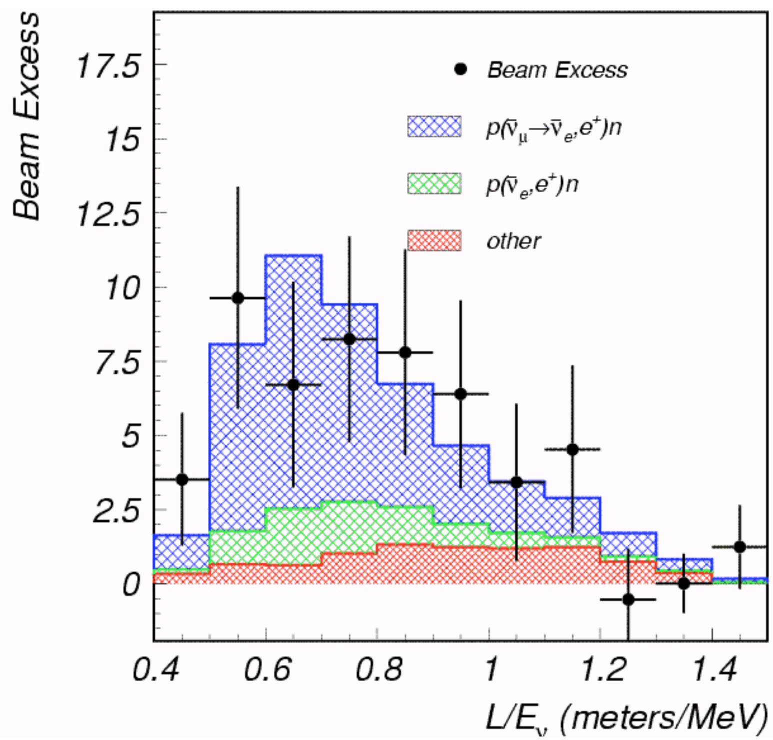


Confirmation with Super-K, K2K and MINOS data

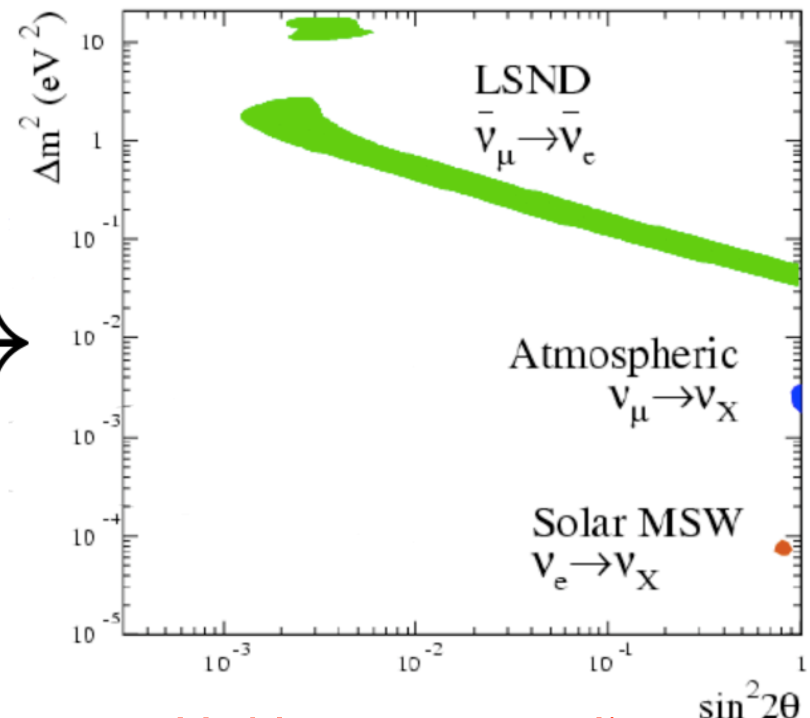


Confirmation with SNO, Kamland data

- LSND: Liquid Scintillator Neutrino Detector (Los Alamos, 1990s)
  - Evidence of $\bar{\nu}_e$ excess in $\bar{\nu}_\mu$ beam



2 ν osc. fit →



LSND excess: 87.9 ± 22.4 ± 6.0 (3.8 σ)

Highly controversial!

- MiniBooNE motivation
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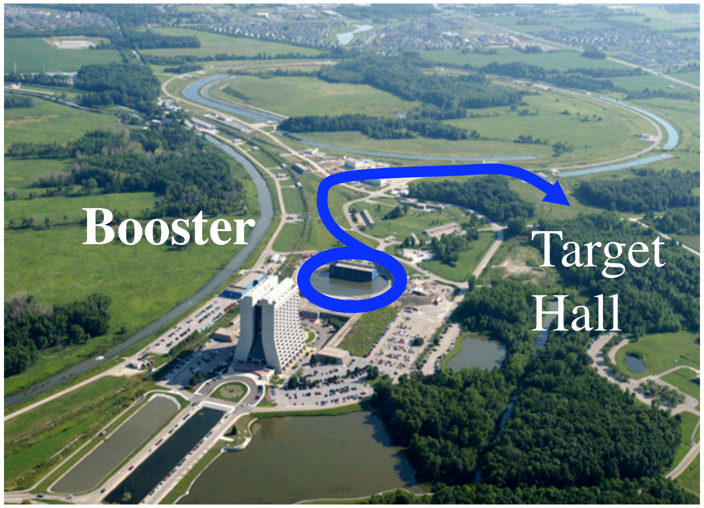
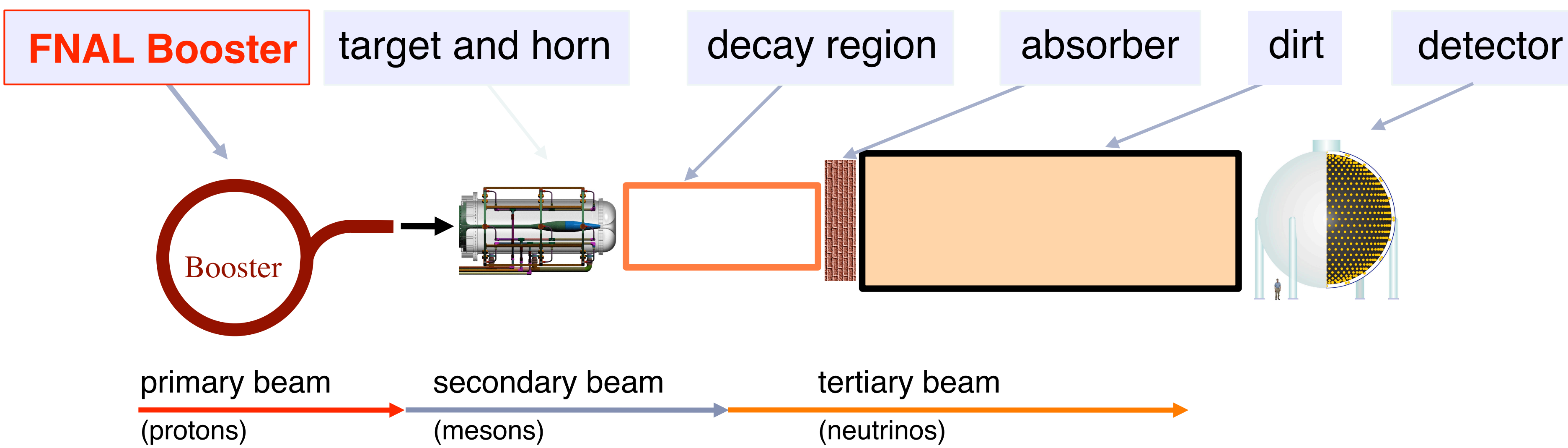
- MiniBooNE has same L/E as LSND but different systematic errors. Quick comparison:

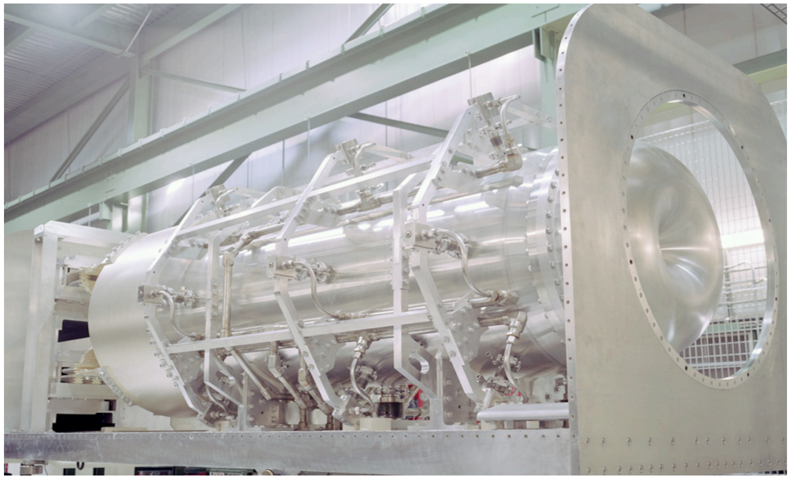
LSND	MiniBooNE
Neutrino beam from accelerator (decay-at-rest, average E_ν ~ 35 MeV)	Neutrino beam from accelerator (decay-in-flight, average E_ν ~ 800 MeV)
ν_μ too low E to make μ or π	New backgrounds: ν_μ CCQE and NC π^0 mis-id for oscillation search
Proton beam too low E to make K	New backgrounds: intrinsic ν_e from K decay (0.5% of p make K)

Booster Neutrino Beam



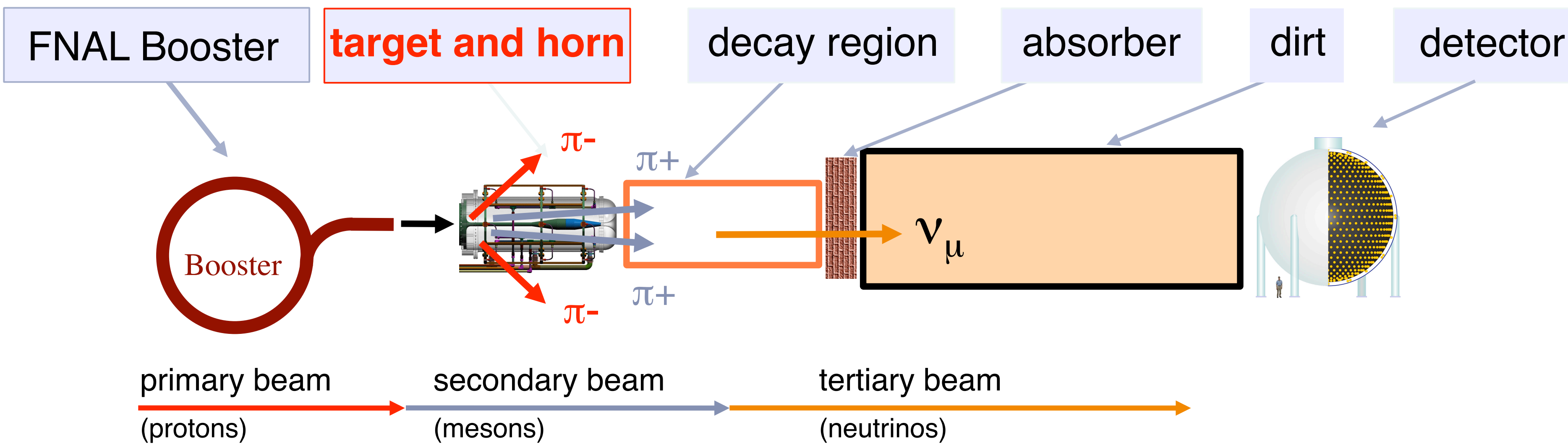
8.9 GeV/c momentum protons extracted from Booster, steered toward a beryllium target



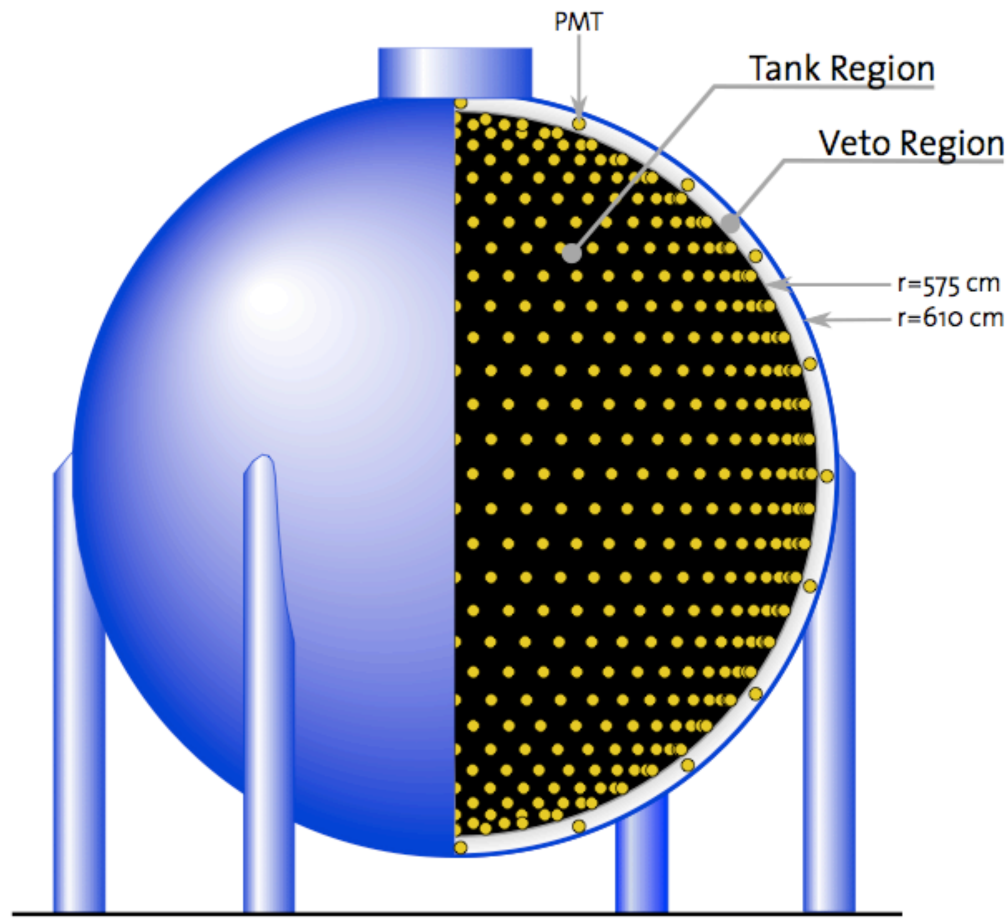


Magnetic horn with reversible polarity focuses either neutrino or anti-neutrino parent mesons

("neutrino" vs "anti-neutrino" mode)



- 6.1m radius Cherenkov detector houses 800 tons of undoped mineral oil, 1520 PMTs in two regions
  - Inner signal region
  - Outer veto region (35 cm thick)



Nucl. Instr. Meth. A599, 28 (2009)

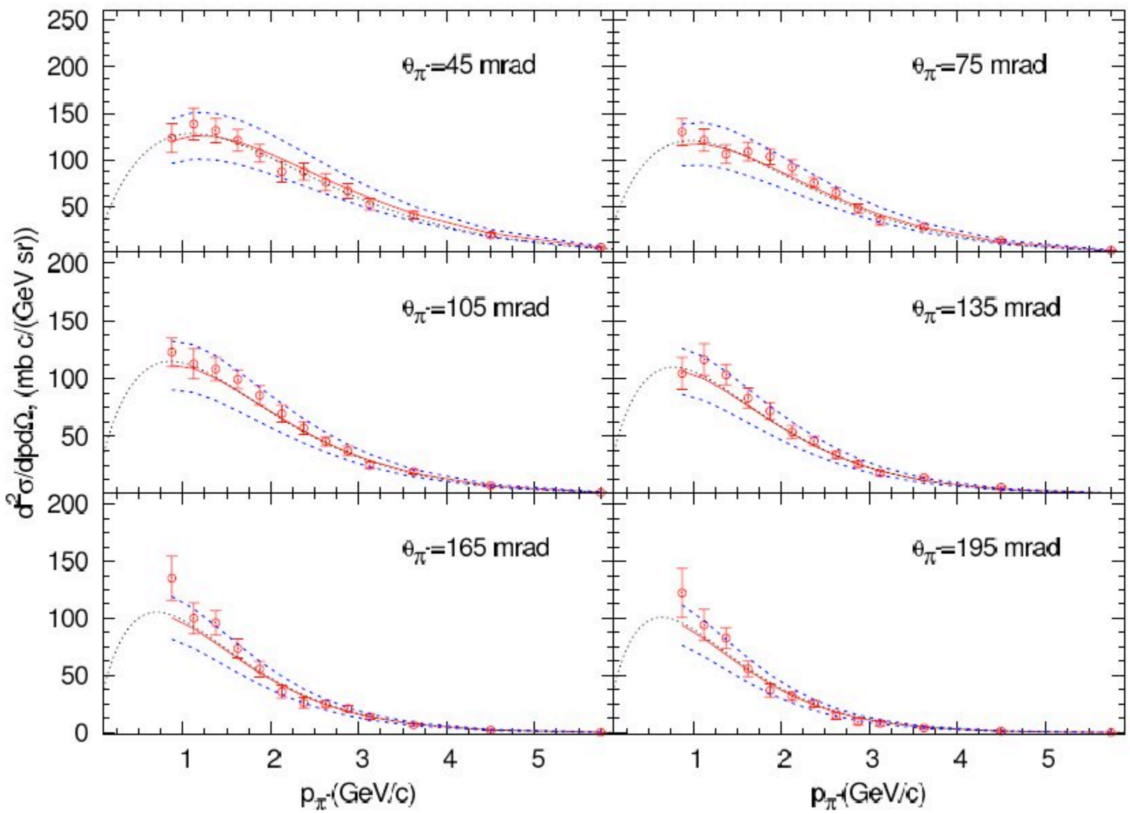
- Flux prediction based exclusively on external data - no *in situ* tuning

- Dedicated π production data taken by HARP collaboration, measured 8.9 GeV/c

$$p + \mathrm{Be} \rightarrow \pi^{\pm} + X$$

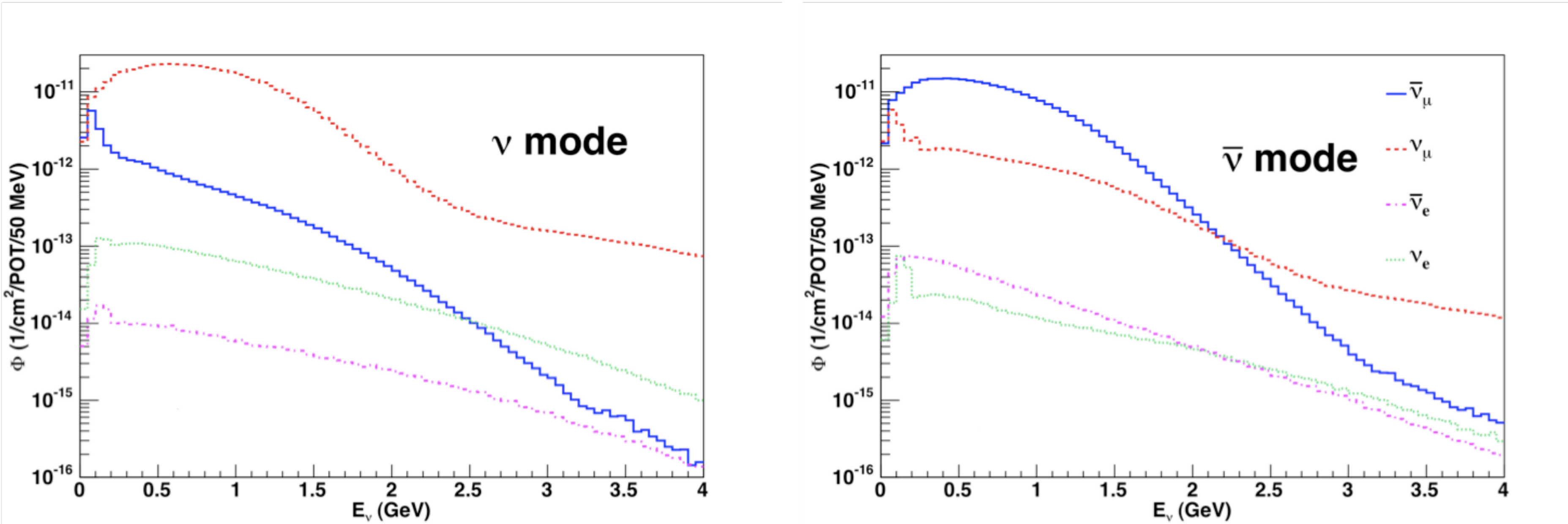
on MiniBooNE replica target

π^- production



HARP collaboration,
Eur. Phys. J. C **52** 29 (2007)

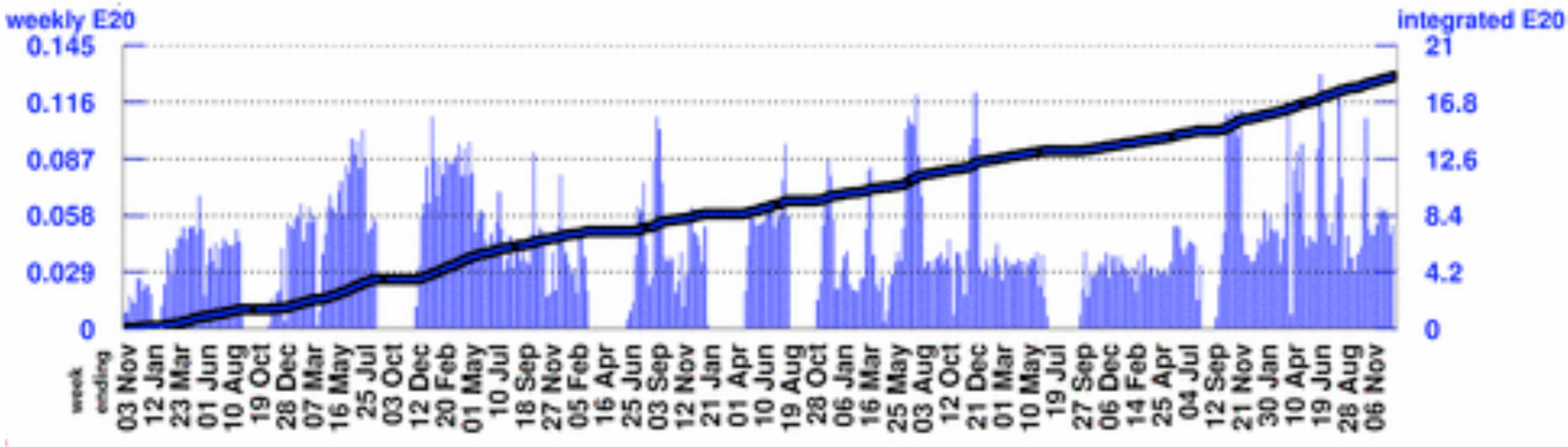
Neutrino Flux



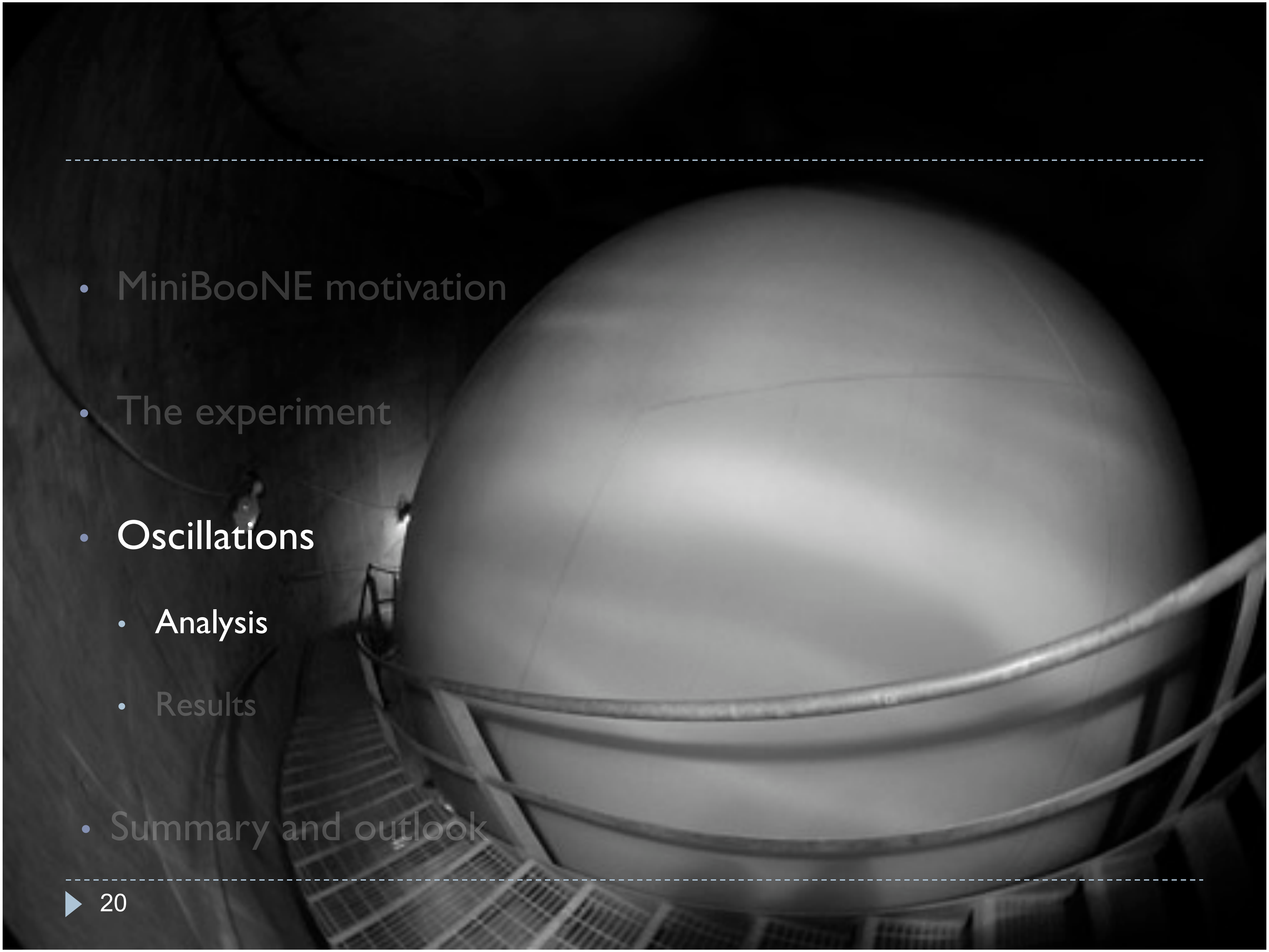
MiniBooNE collaboration,
Phys. Rev. D **79**, 072002 (2009)

- Combining HARP data with detailed Geant4 simulation gives the flux prediction at the MiniBooNE detector for positive and negative focusing horn polarities

A BooNE of Data



- Stable running since 2002
- POT received from Booster:
  - 6.4×10^{20} in ν mode
  - 8.6×10^{20} in $\bar{\nu}$ mode (analyzed), ~30% more data coming!



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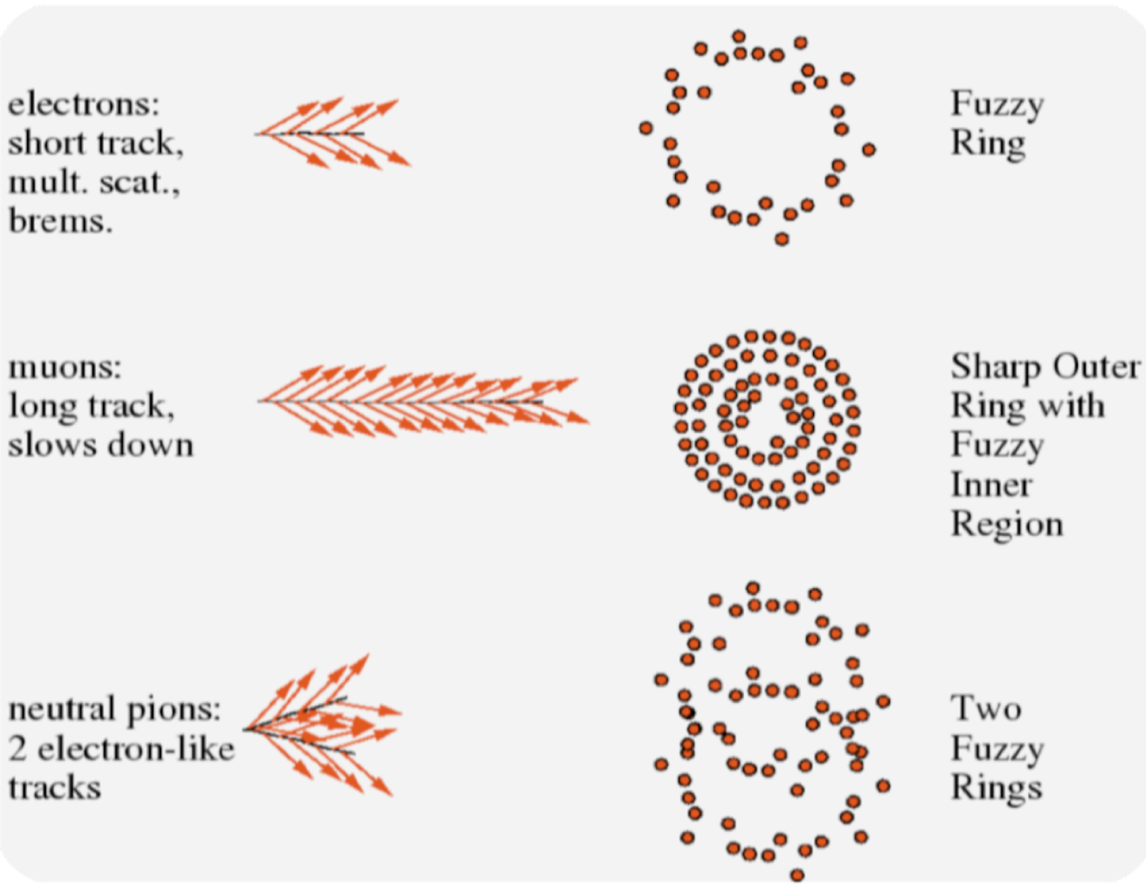
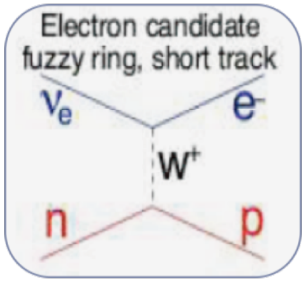
Particle ID Basics

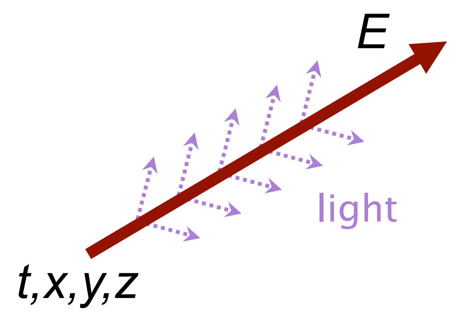
- PID based almost exclusively on timing and topology of PMT hits



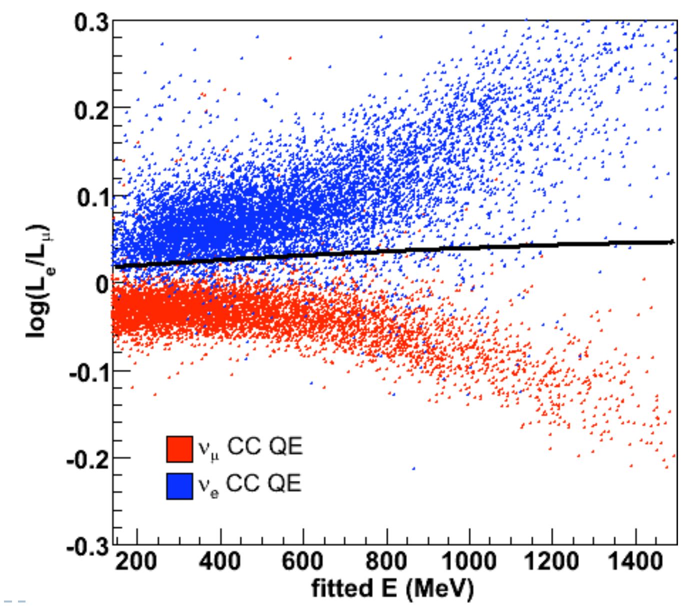


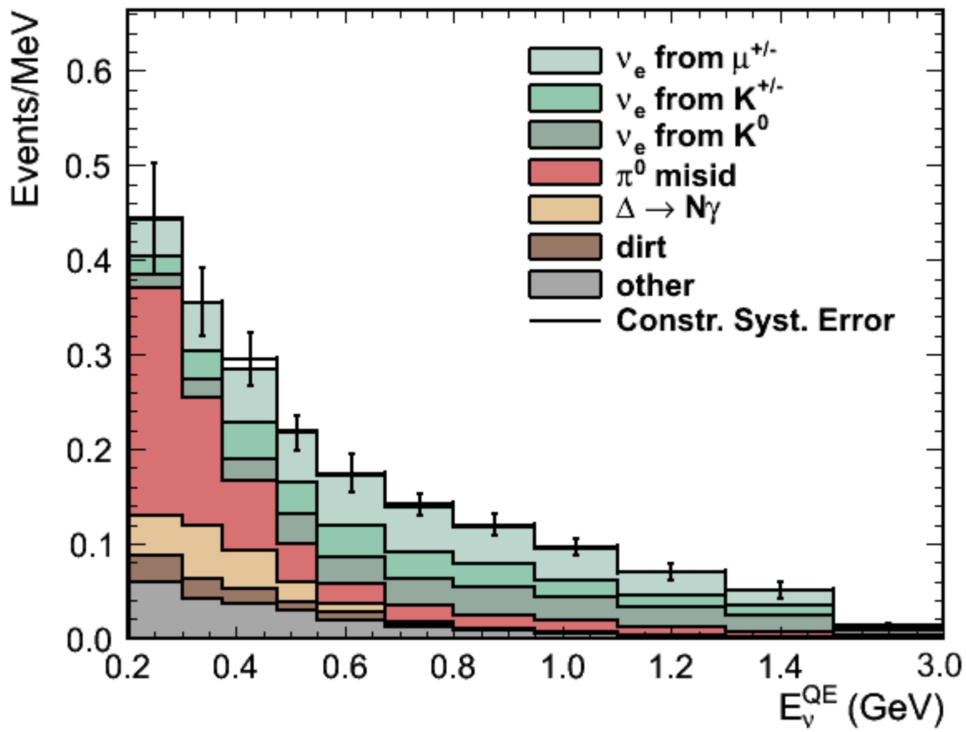
Particle ID Analysis

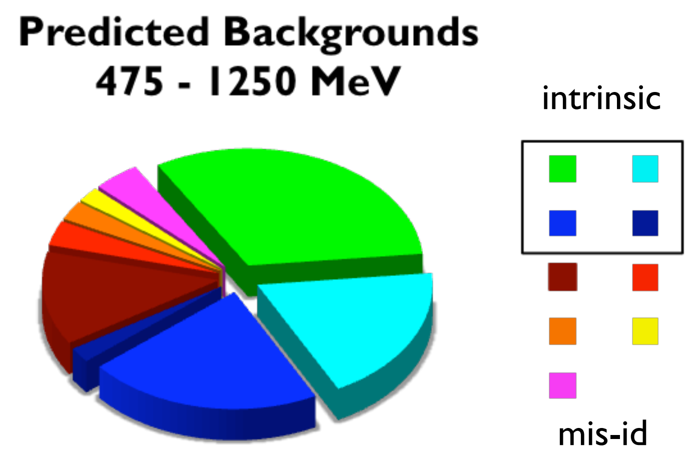
- Form charge and timing PDFs, fit for track parameters under 3 hypotheses
  1. Electron
  2. Muon
  3. Superposition of two γ's from π^0 decay

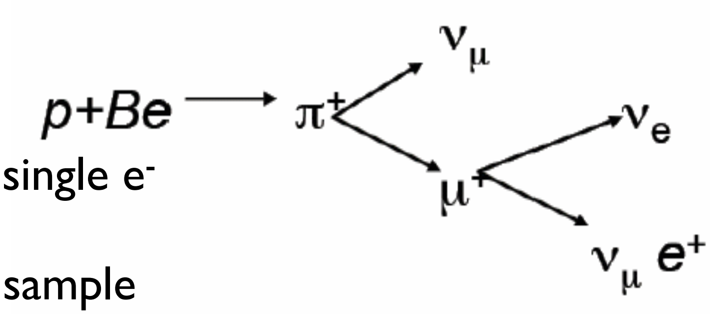


- Apply energy-dependent cuts on L(e/μ), L(e/π) and π^0 mass to search for single electron events
- Plot events passing cuts as a function of reconstructed ν_e energy and fit for two-ν oscillations







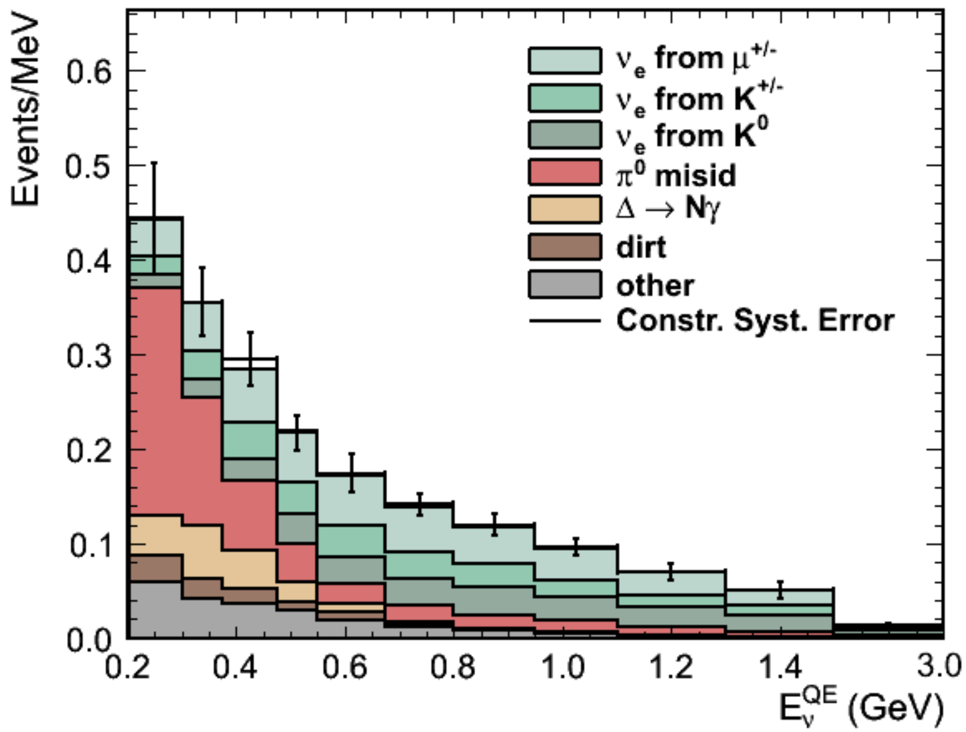


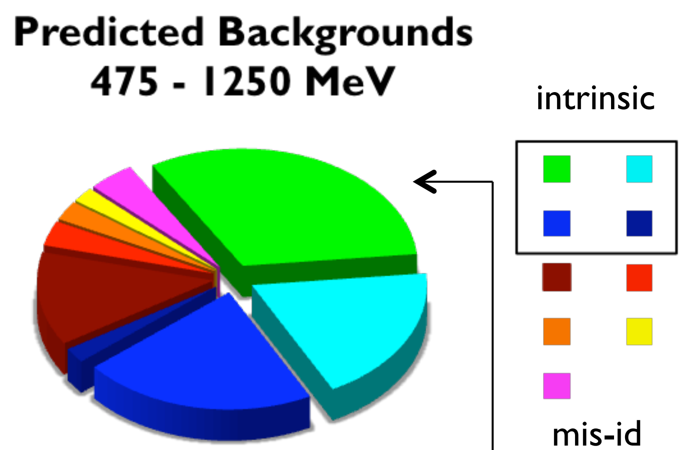
Signal interaction ν_e CCQE: $\nu_e + n \rightarrow e^- + p$, observe single e^-

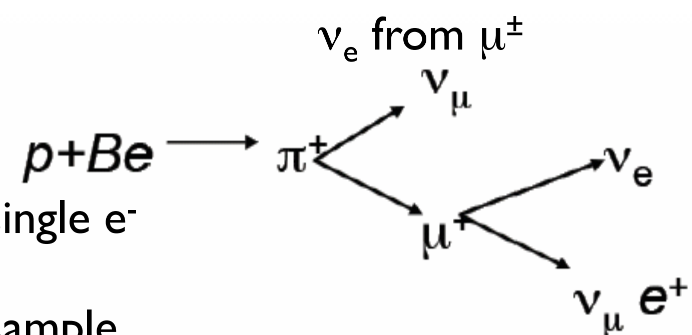
Intrinsic ν_e from μ originate from same π as ν_μ CCQE sample

Measuring ν_μ CCQE channel constrains intrinsic ν_e from $\pi \rightarrow \mu \rightarrow e$ decay

Backgrounds







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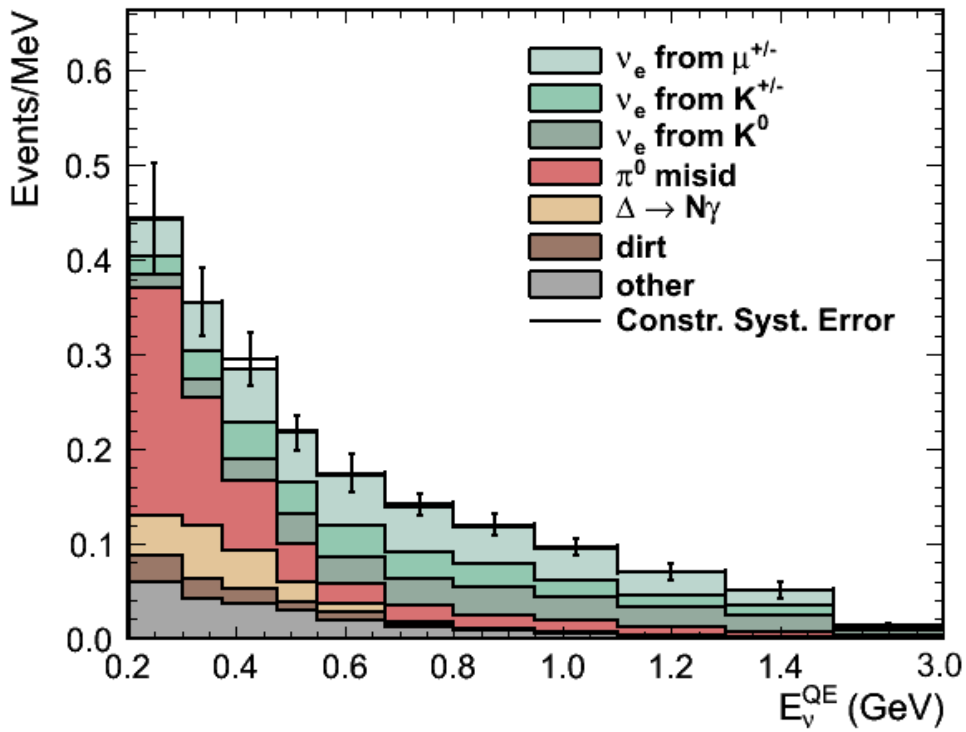
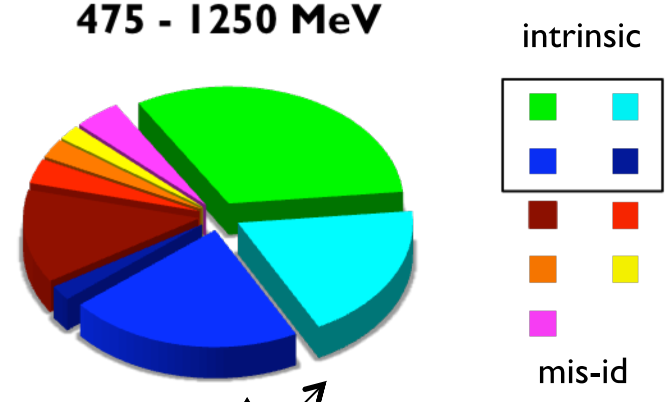


Predicted Backgrounds
475 - 1250 MeV

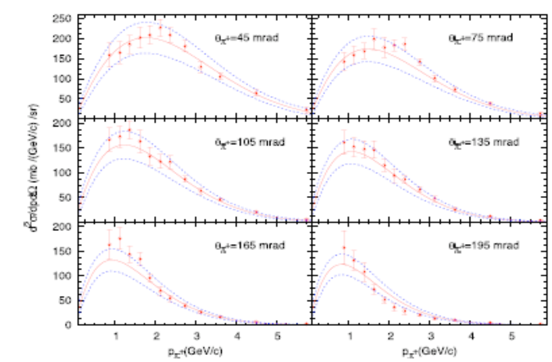


ν_e from $K^\pm$, K^0

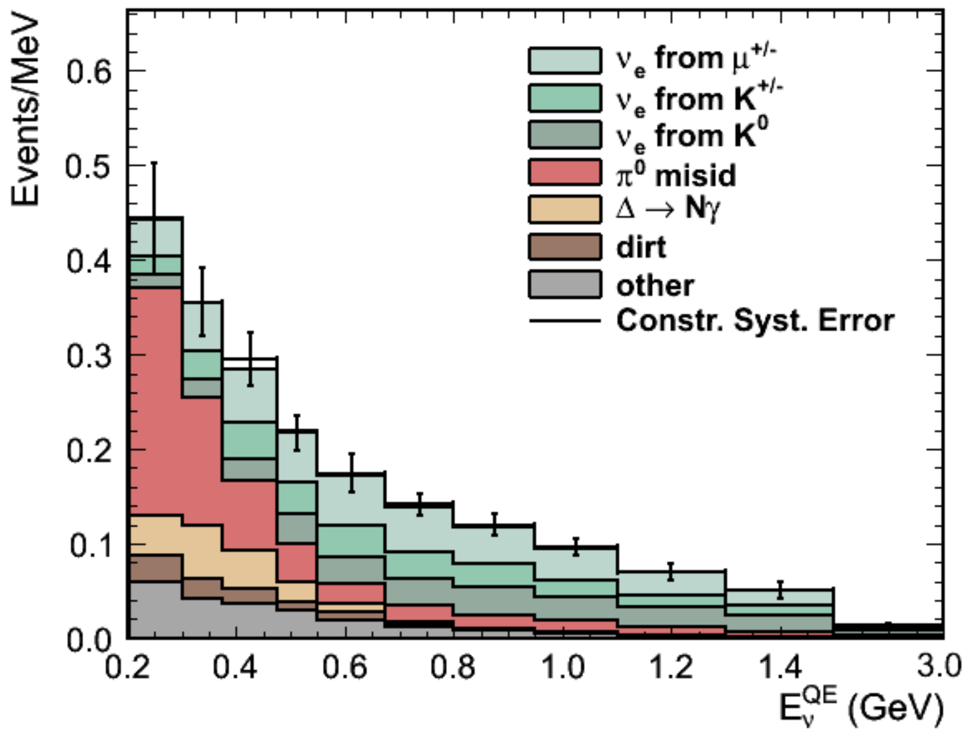
At high energy, ν_μ flux is dominated by K production

Measuring ν_μ CCQE at high energy constrains kaon production, and thus intrinsic ν_e from K

Also use external measurements from HARP



Sanford-Wang fits to world K^+/K^0 data



Measured in MiniBooNE

Predicted Backgrounds
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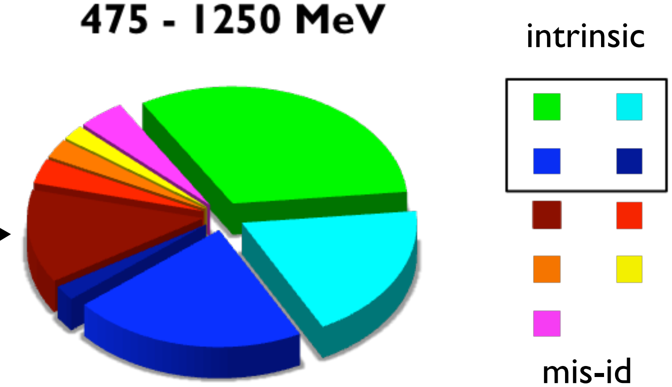
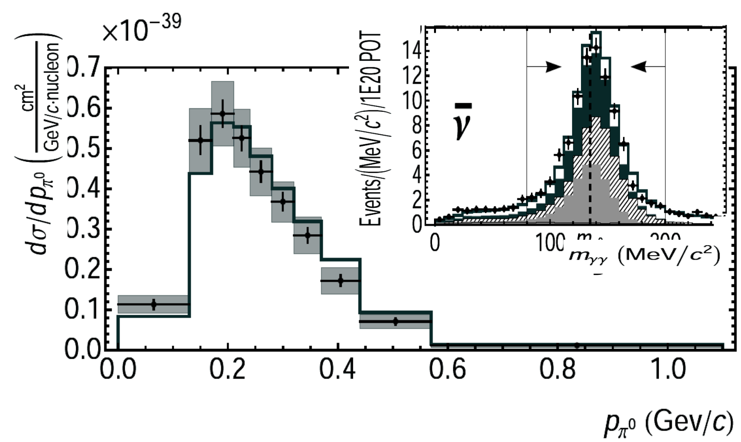
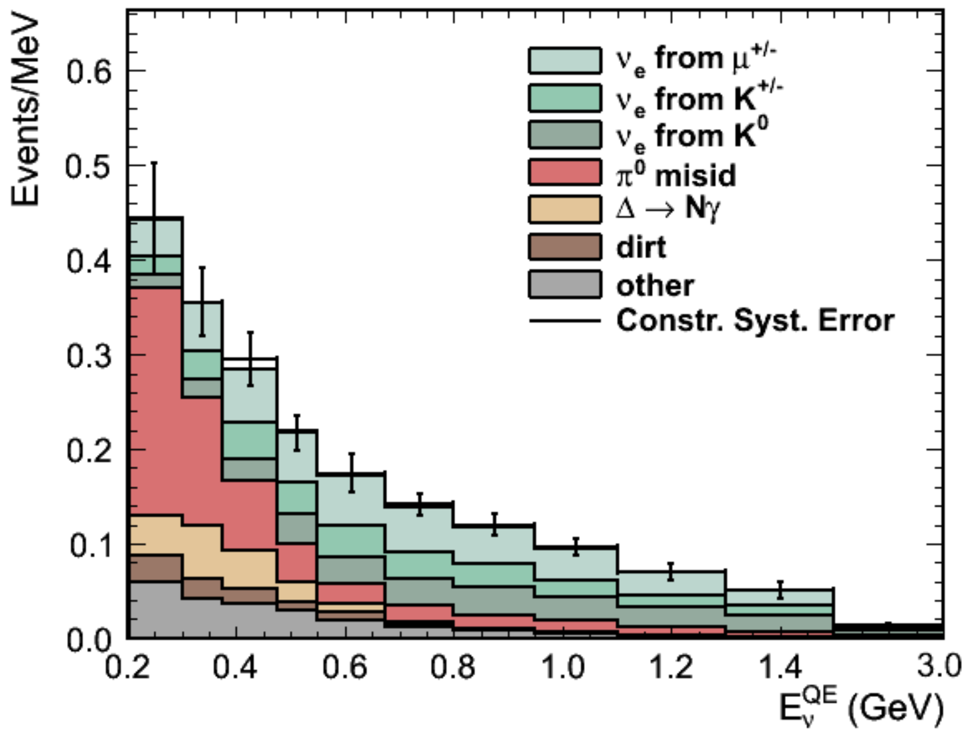
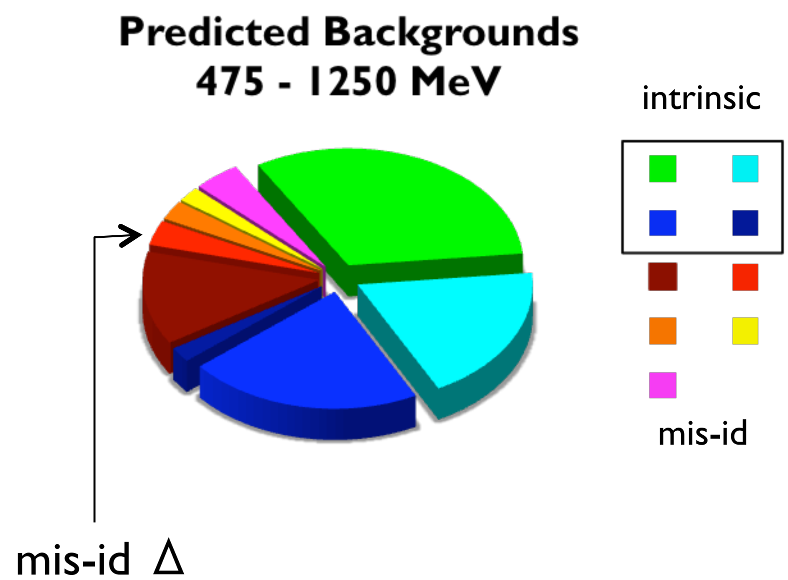


mis-ID π^0



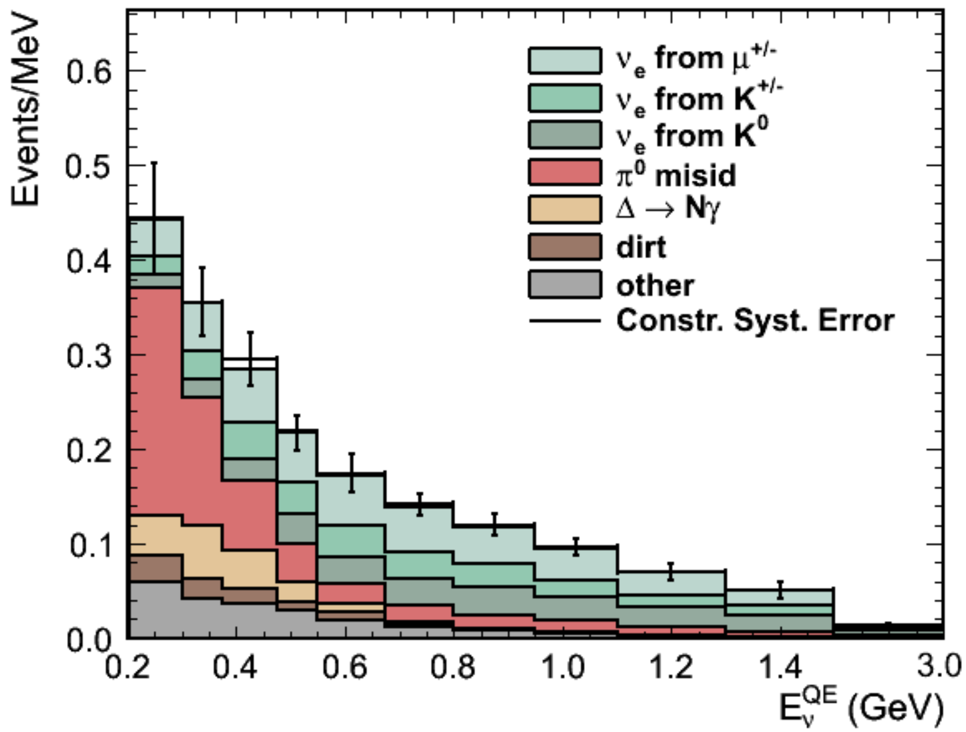
Backgrounds





About 80% of our NC π^0 events come from resonant Δ production

Constrain $\Delta \rightarrow N\gamma$ by measuring the resonant NC π^0 rate, apply known branching fraction to N, including nuclear corrections



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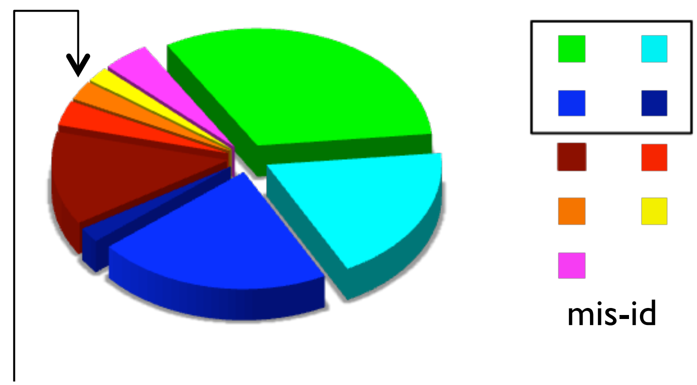
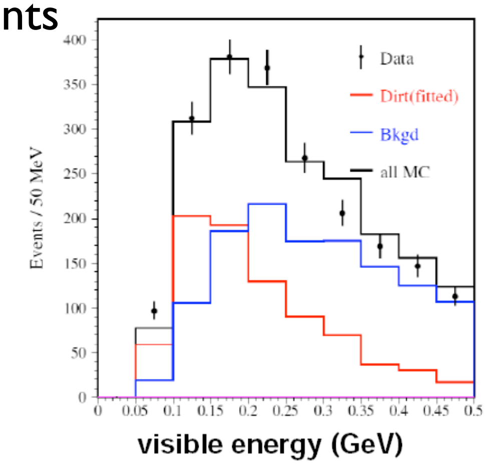


dirt events

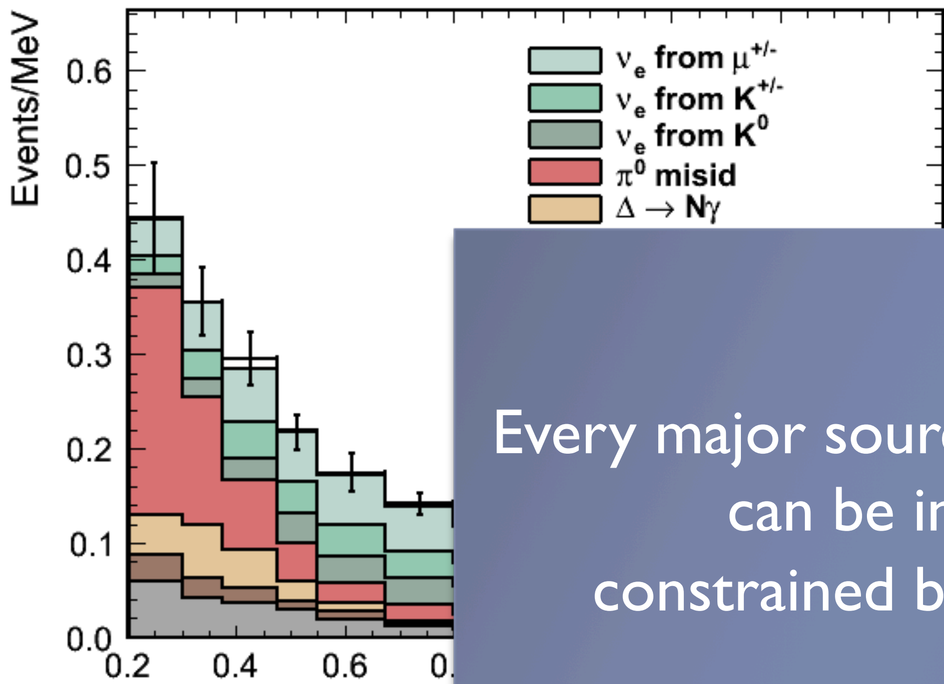


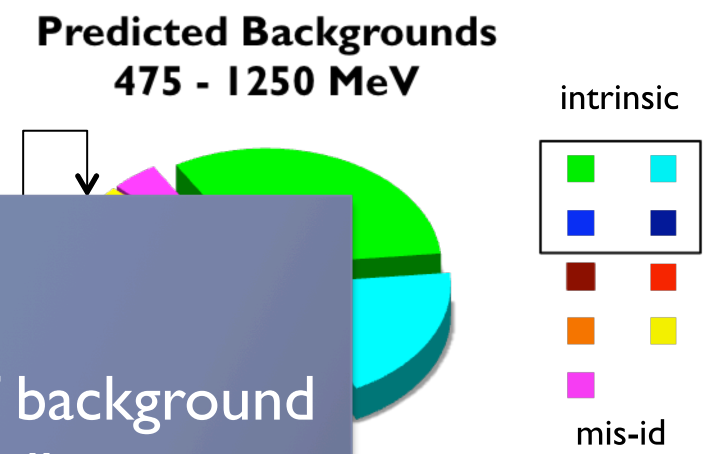
Come from ν events in surrounding dirt

Pileup at high radius and low E

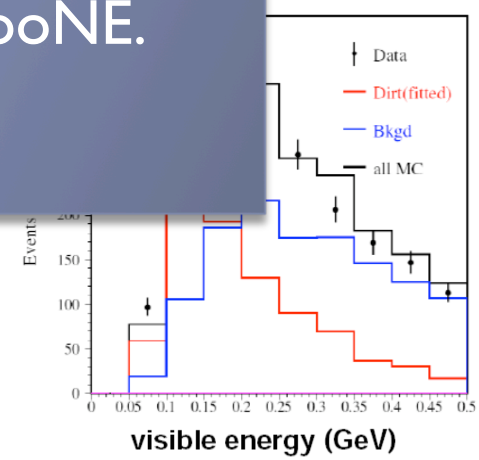
Fit dirt-enhanced sample to extract dirt event rate with 10% uncertainty

Backgrounds





Every major source of background can be internally constrained by MiniBooNE.



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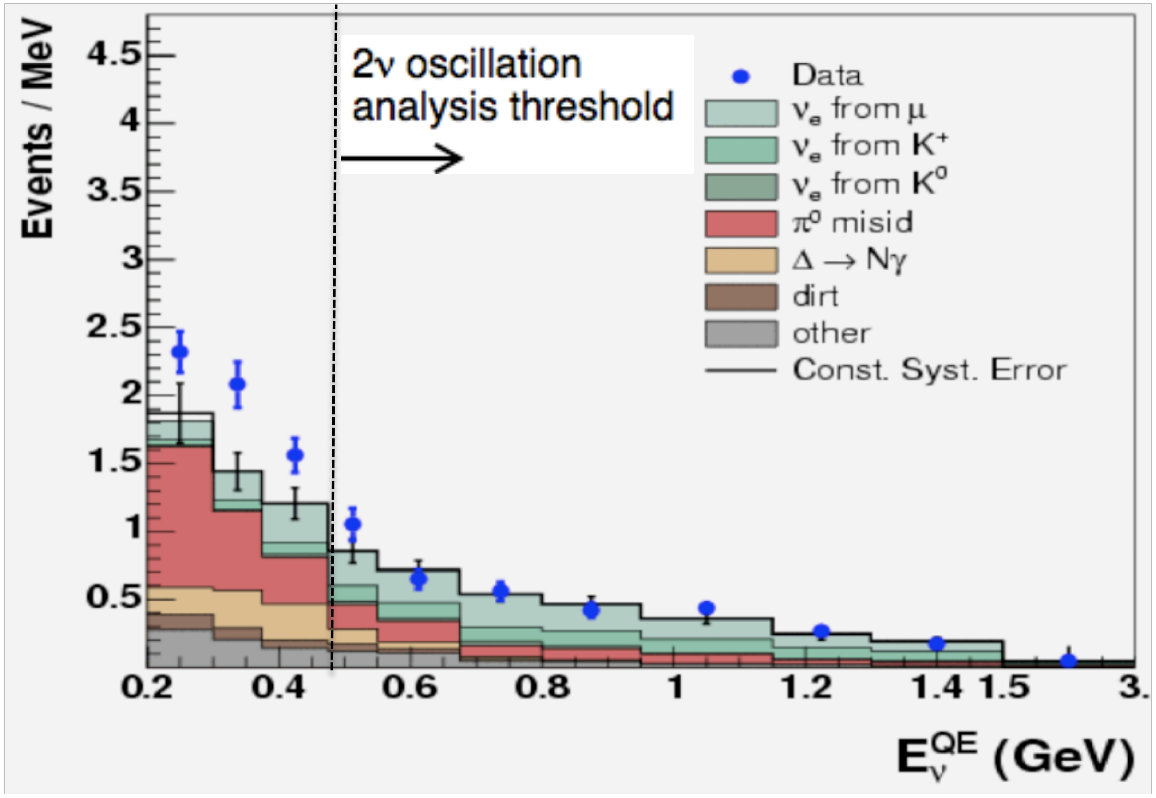
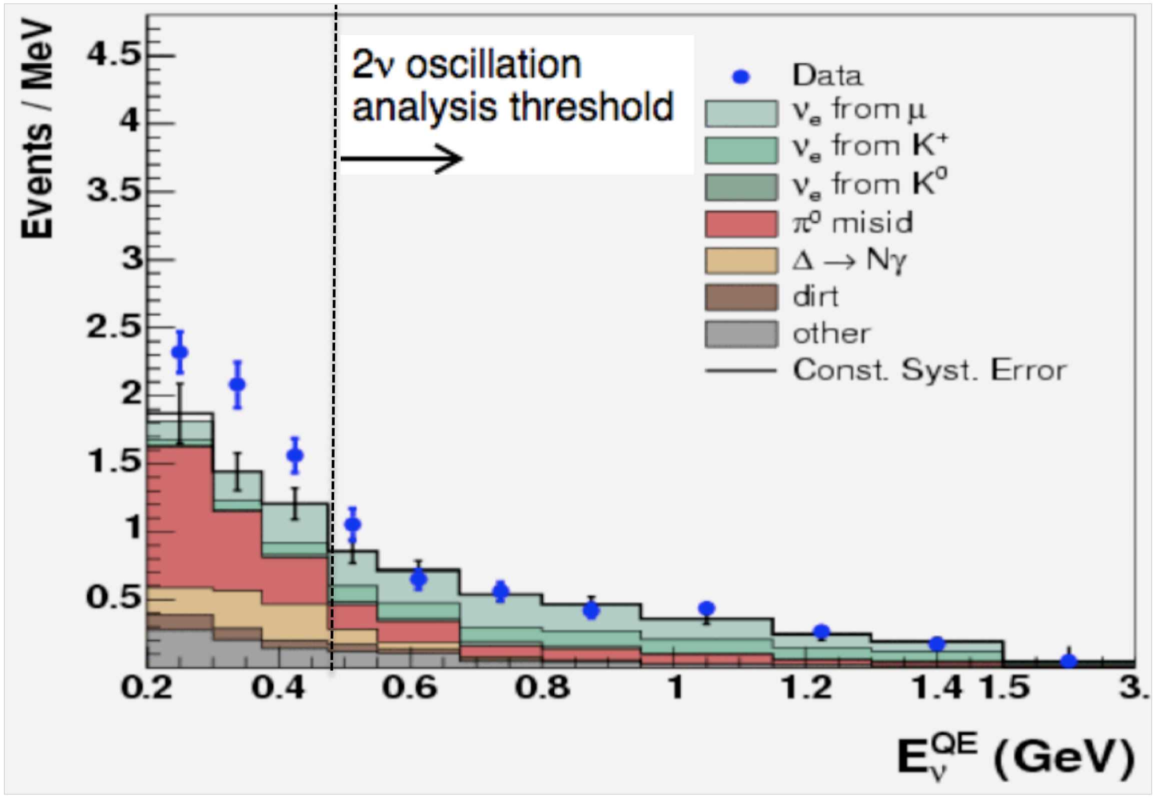


Surprise!

Neither perfect agreement with background nor LSND-like signal!

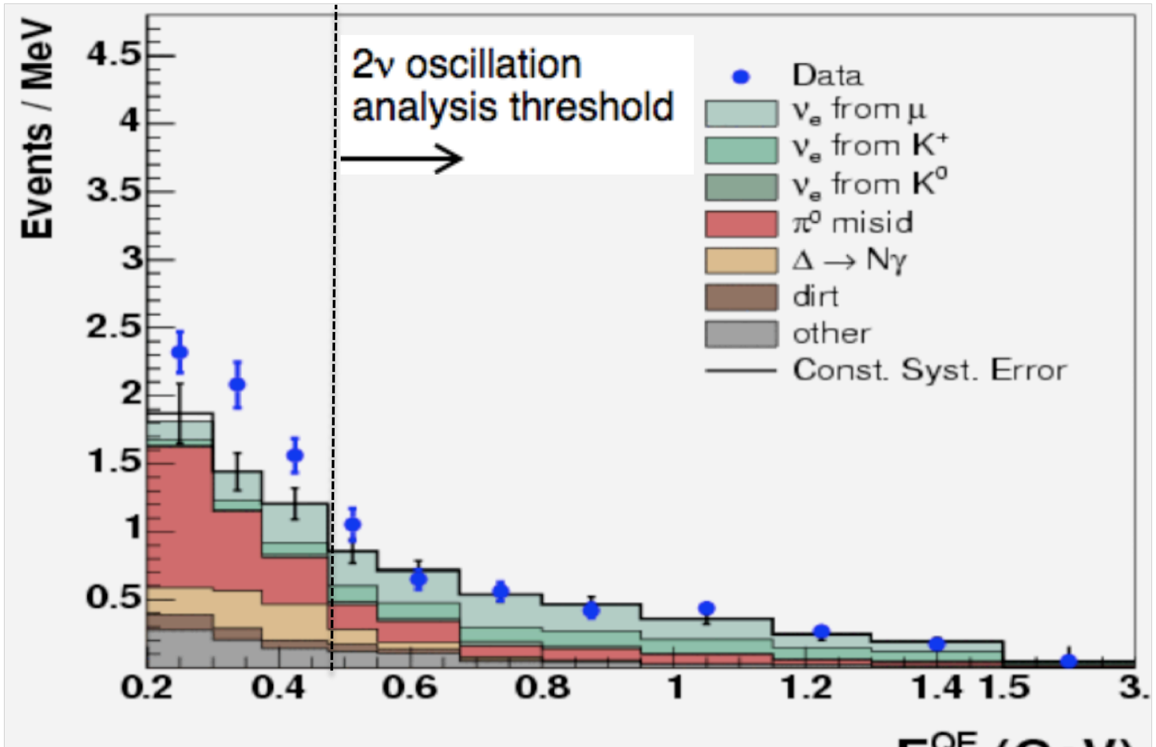
$\nu_\mu \rightarrow \nu_e$ Appearance Data!



Below 475 MeV

Excess is 128 ± 20 (stat) ± 39 (syst) events (3σ excess)

Shape inconsistent with 2ν oscillation interpretation of LSND



Above 475 MeV

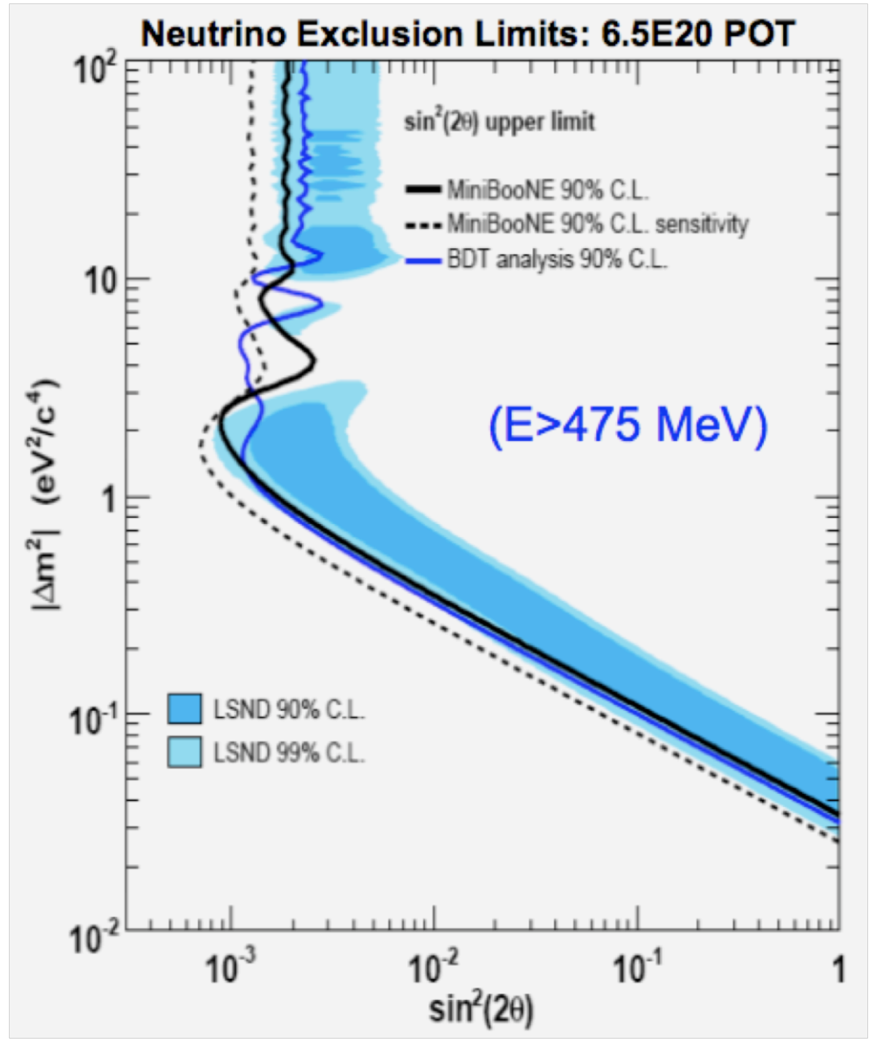
Excellent agreement with background predictions

Region of highest sensitivity to an LSND-like 2ν mixing hypothesis, use it to exclude that model assuming CP conservation

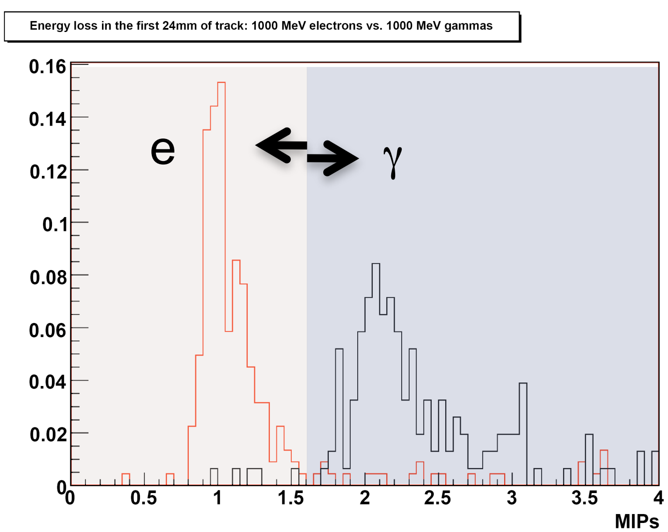
Observe 408 events, expect 386 ± 20 (stat) ± 30 (syst)

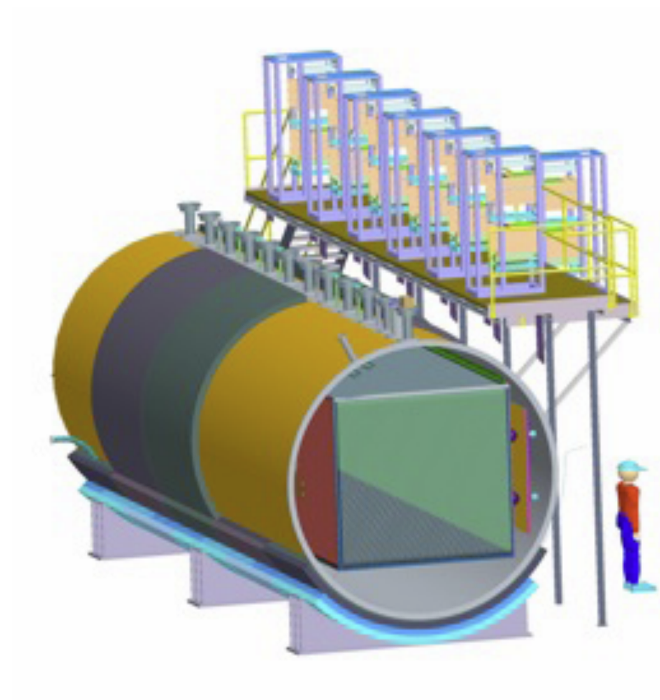
$\nu_\mu \rightarrow \nu_e$ Appearance Data!

- Neutrino-mode appearance analysis excludes LSND-like oscillations at 90% CL

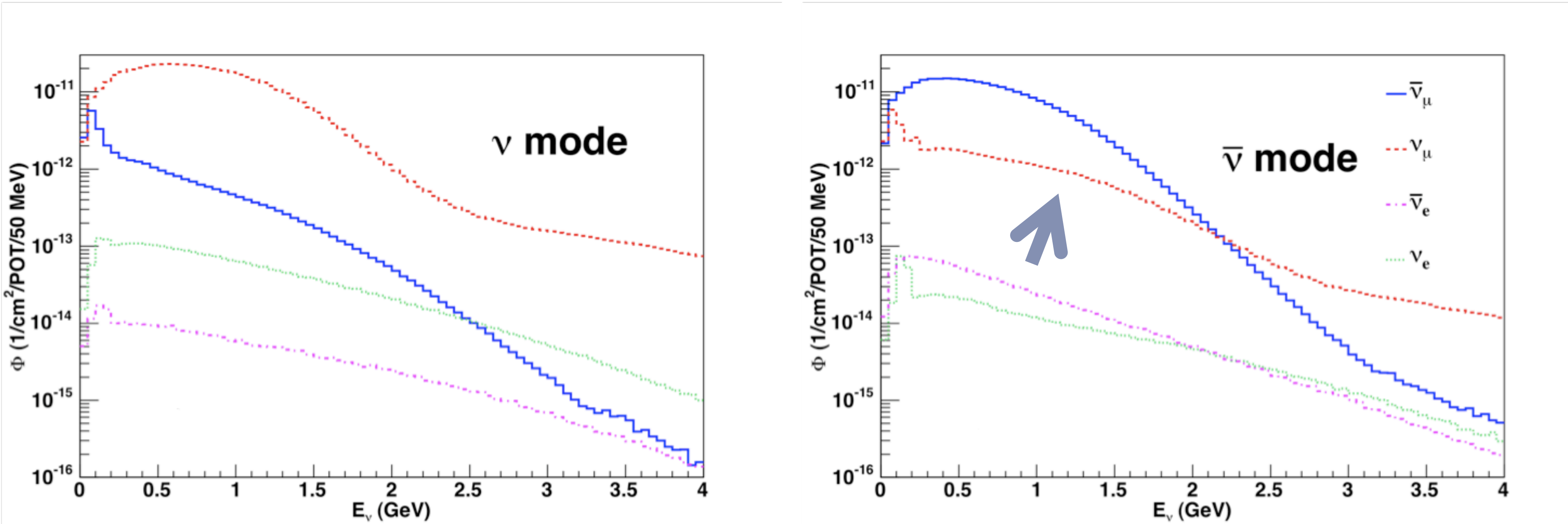


- Low E excess either unexpected background or new physics - must be explained! Ambiguous between e, γ-like events
- MicroBooNE: next-generation liquid argon TPC with excellent e/γ resolution





- Construction expected soon

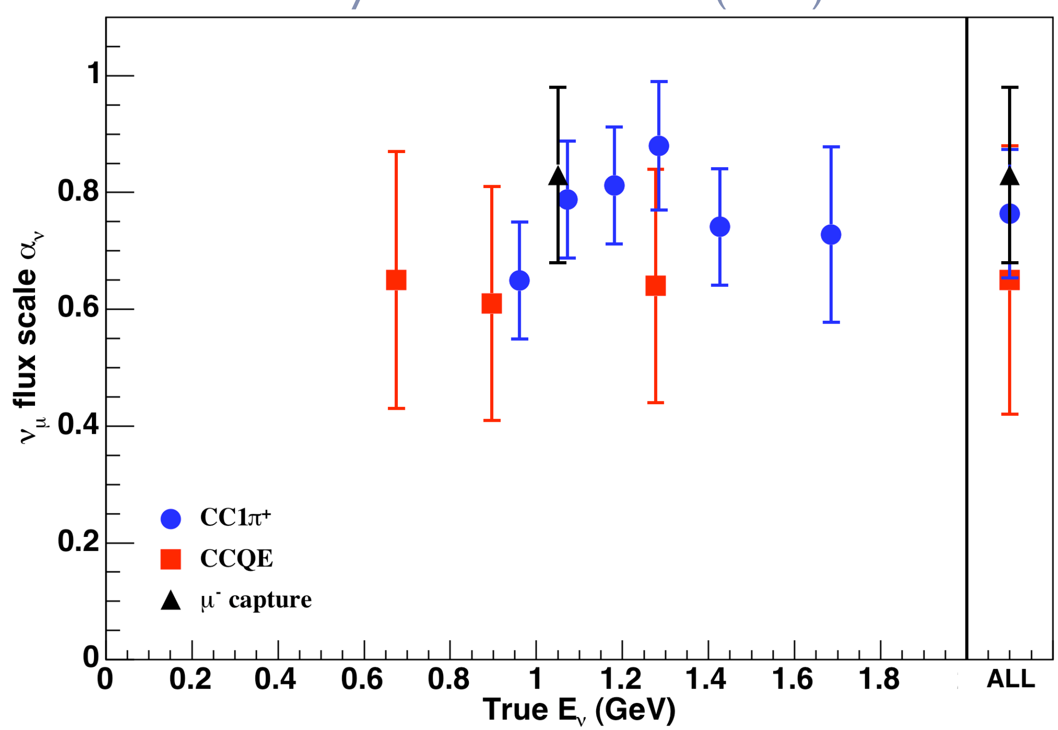


Phys. Rev. D **79**, 072002 (2009)

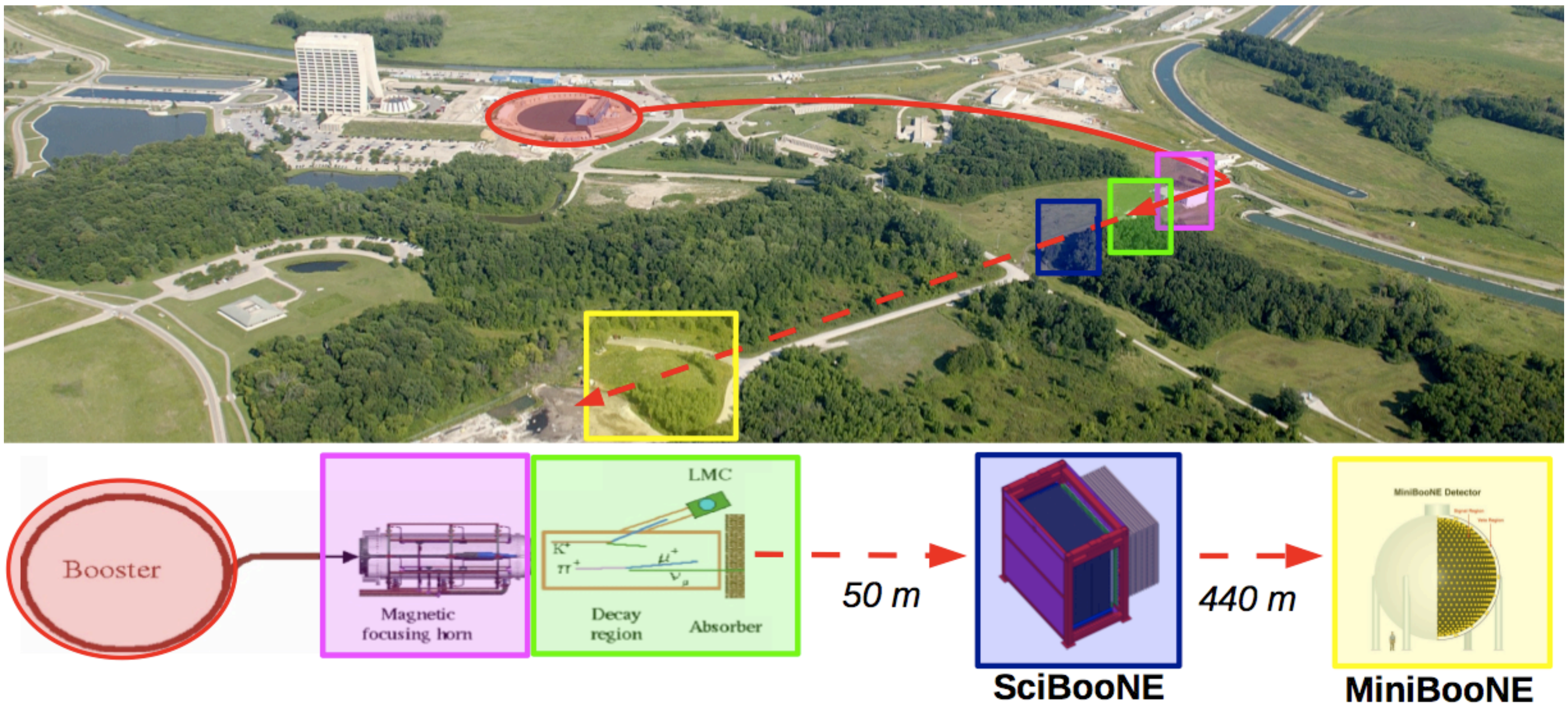
- Significant neutrino content in anti-neutrino beam
- Detector not magnetized; cannot separate contribution based on μ charge

- First measurement of neutrino contribution to anti-neutrino beam with non-magnetized detector
- **3 independent, complementary** measurements
  - μ^+/μ^- angular distribution
  - π^- capture
  - μ^- capture
- Demonstration of techniques for other non-magnetized detectors looking for $\cancel{CP}$
  - NOνA, T2K, LBNE, etc.

Phys. Rev. D81: 072005 (2011)



- SciBooNE: a fine-grained tracking detector 50m downstream of proton target in same ν beam



- SciBooNE provides powerful check of upstream beam content

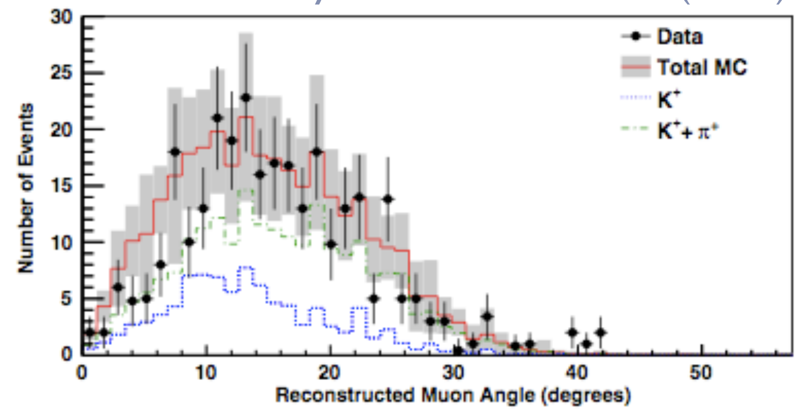
Updates to Anti-Neutrino Analysis: Flux Revisited

- Tracking power of SciBooNE allows sensitivity to ν parent rates through track multiplicity

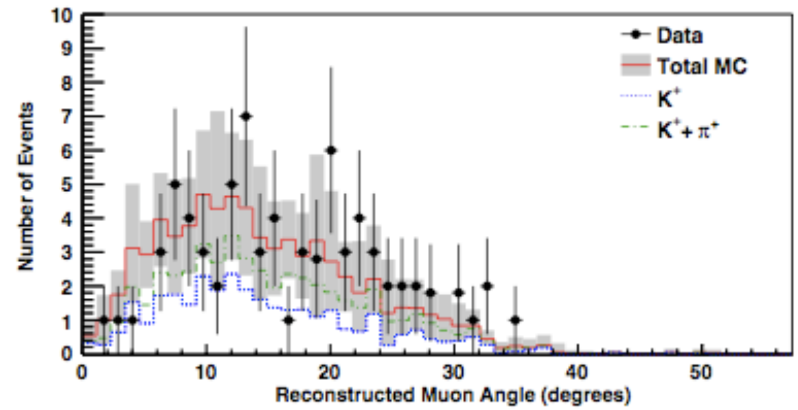
- More visible tracks -> higher energy ν's
  - one track: mostly μ-only
  - two: μ + hadron
  - three: μ + 2 hadrons

- Extracted K^+ rate: 0.85 ± 0.11
  - applied to MiniBooNE $\bar{\nu}$ analysis

Phys. Rev. D84: 012009 (2011)

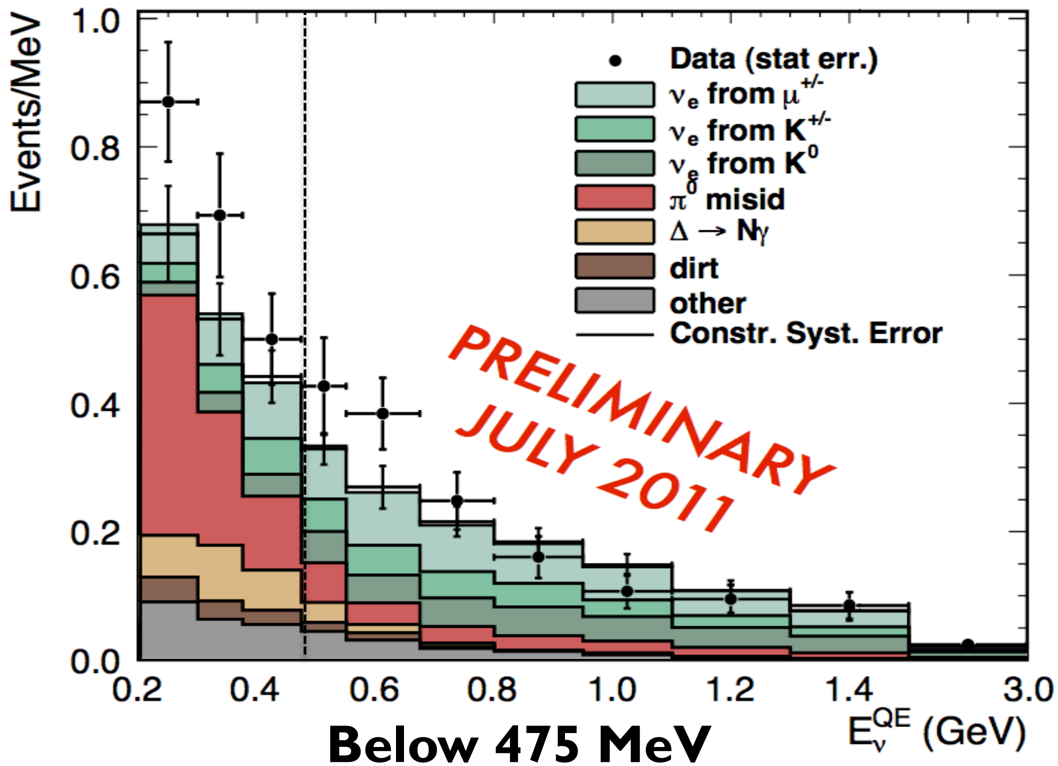


(b) 2-Track Sample



(c) 3-Track Sample

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance Data!



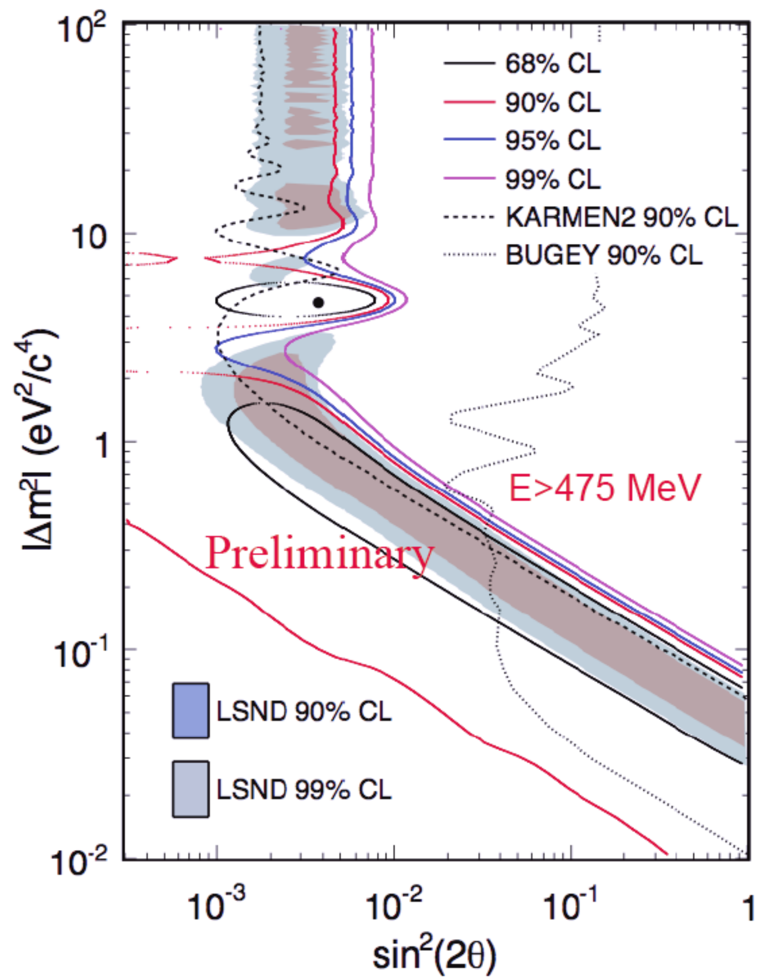
Below 475 MeV

38.6 ± 18.6 excess events

Entire energy region

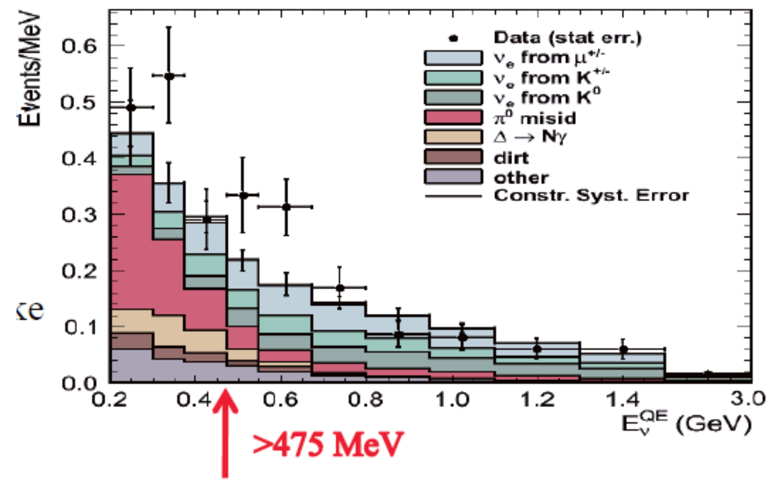
57.7 ± 28.5 excess events

- Data favors 2ν oscillation fit over null hypothesis at 91.1% CL
  - (Fit above 475 MeV)

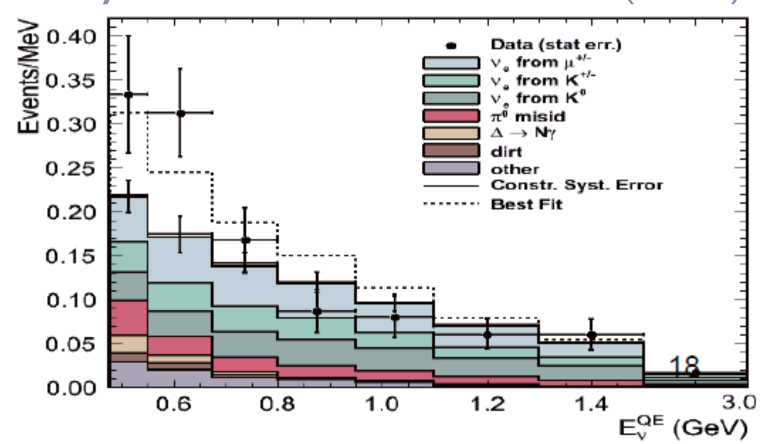


2010 $\bar{\nu}_e$ Appearance (5.66e20 POT)

- “LSND is right?!?”
- E_ν < 475 MeV:
  - 1.3σ excess (by counting)
- E_ν > 475 MeV:
  - 1.5σ excess (by counting)
  - Fit to 2ν osc. prefers BF over null at 99.4%
- Fluctuations happen!
  - ambiguous which direction which data set fluctuated, of course



Phys. Rev. Lett. 105: 181801 (2010)

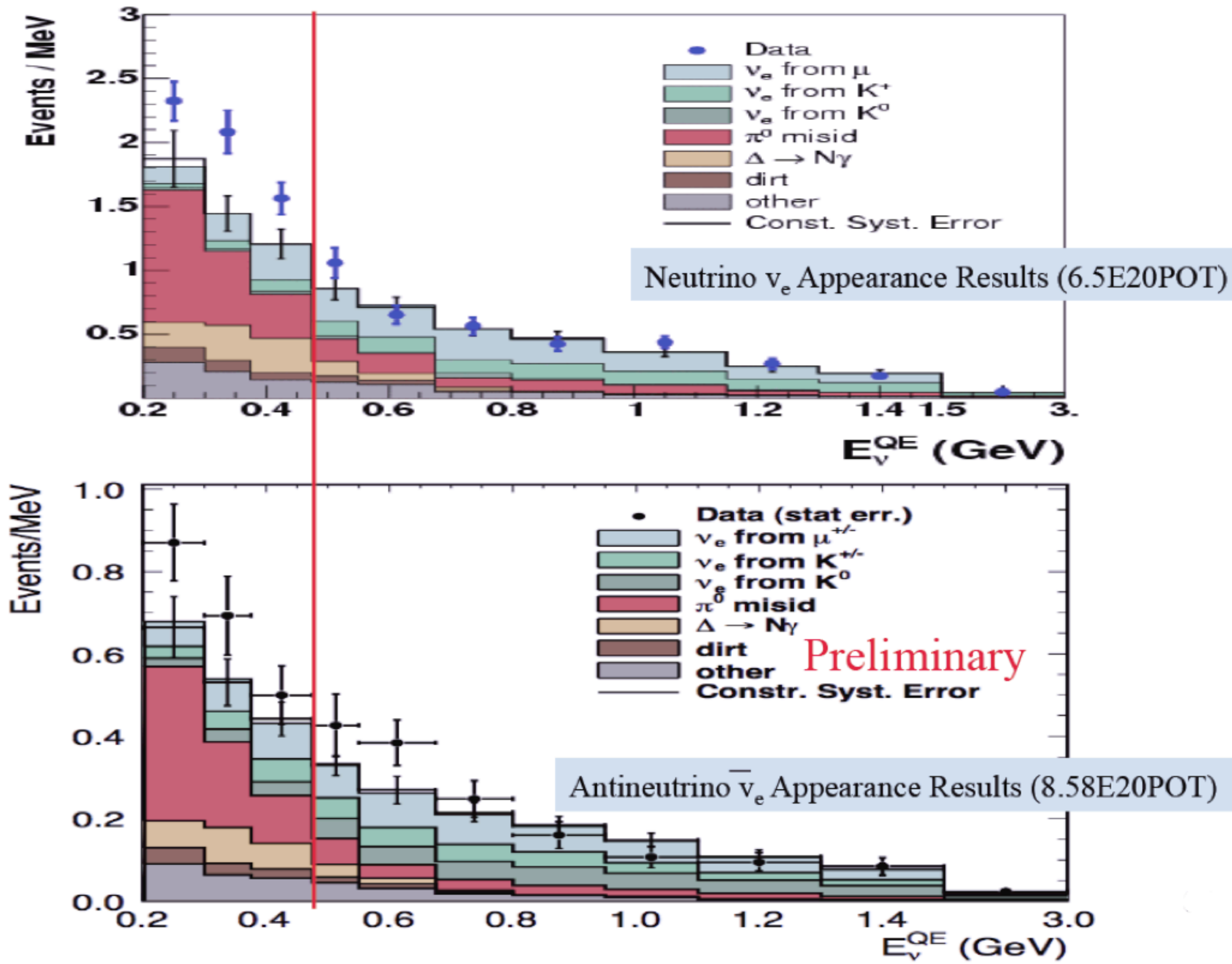


Both (Current) Data Sets

ν_e, $\bar{\nu}_e$ appearance comparison

combined ν_e, $\bar{\nu}_e$ analysis underway

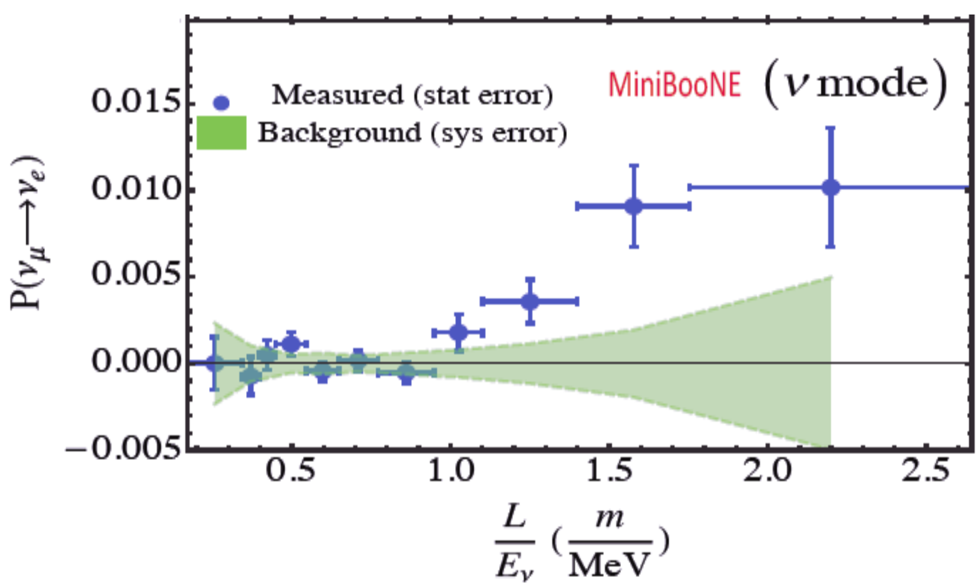
(CP violating model)

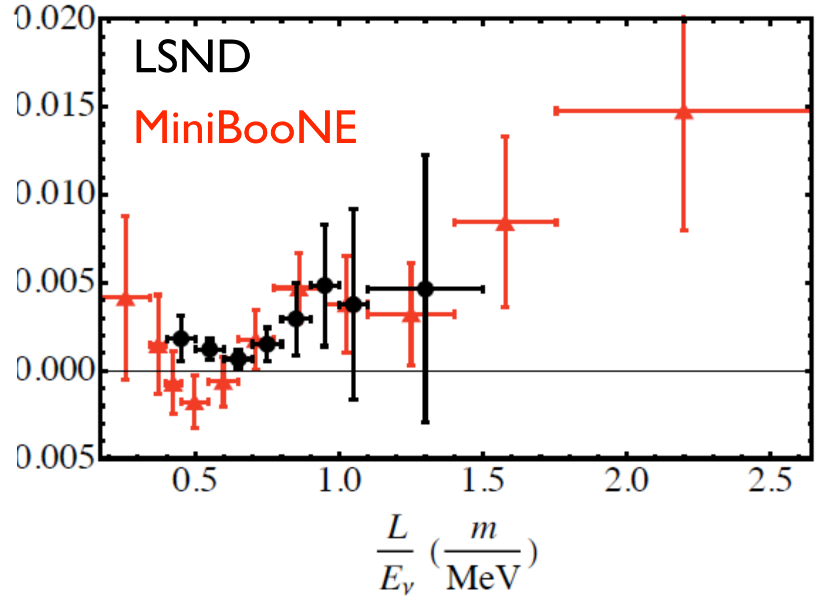


Both Data Sets

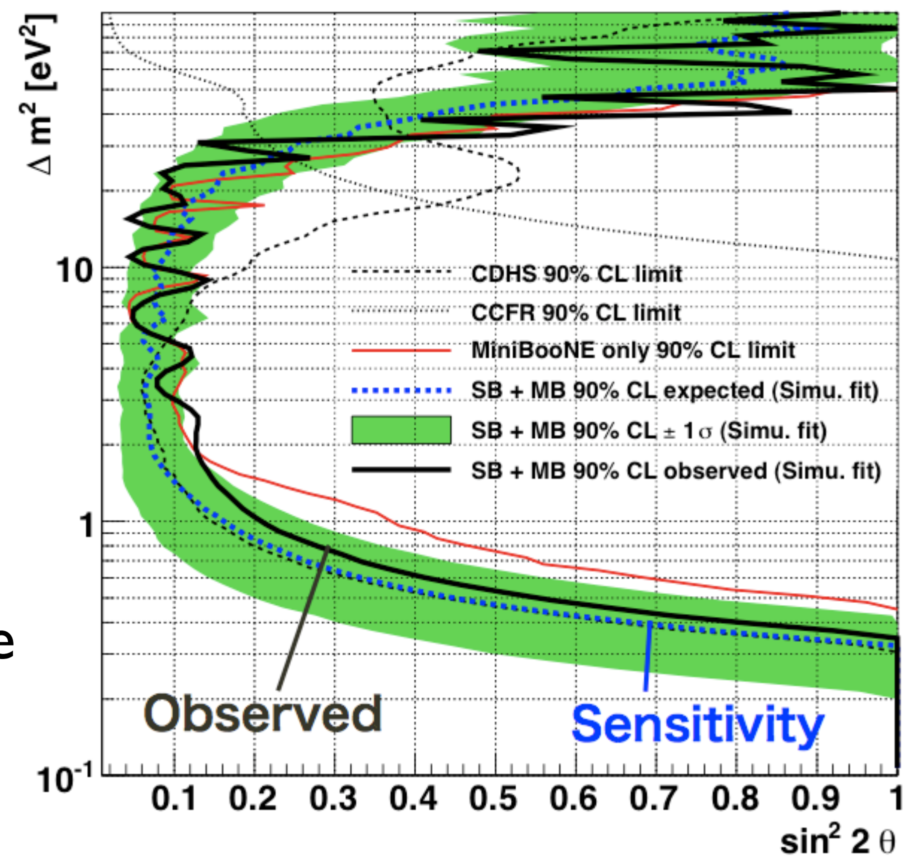
- Model independent comparison to LSND: L/E

ν $\bar{\nu}$





- By comparing rate and shape information in ν_μ CC interactions between the two detectors, set limits for ν_μ disappearance
  - world's strongest limit at $10 < \Delta m^2\ (eV^2) < 30$
- Constrains $\nu_\mu \rightarrow \nu_e$ oscillations as well as other, more exotic models
  - extra dimensions, ~~CPT~~
- Forthcoming $\bar{\nu}_\mu$ disappearance analysis

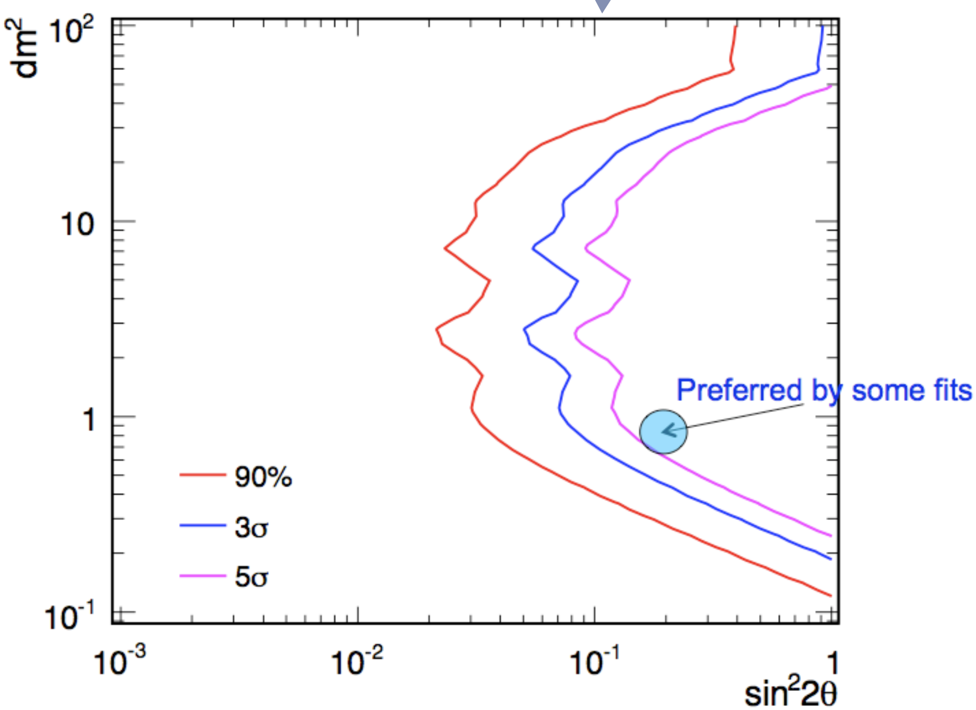


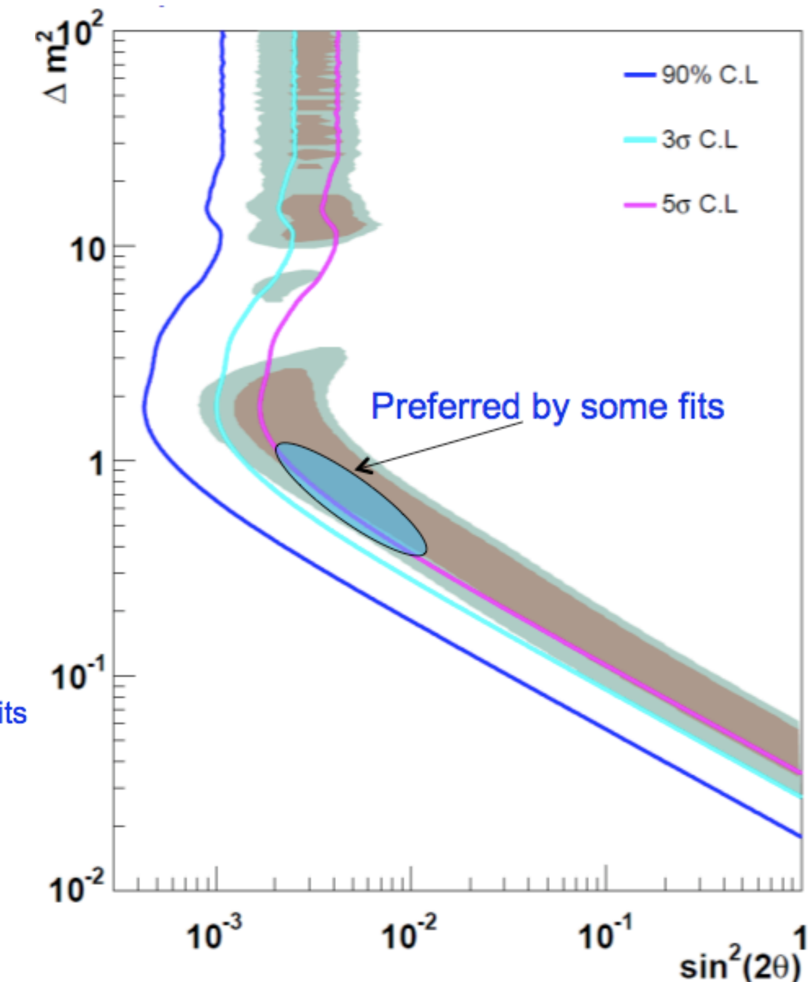
arxiv: 1106.5685

- Common ν beam and ν nuclear target, so many systematic errors cancel! Majority of remaining is MiniBooNE detector error

- New BooNE proposal: MiniBooNE-like near detector for more sensitive osc. measurements (LOI: 0910.2698)

- sensitivity with 1yr running at L = 200m (current MB L ~540m)
  - ν_e appearance
  - ν_μ disappearance





(LOI: 0910.2698)

- MiniBooNE motivation
- The experiment
- Oscillations
  - Analysis
  - Results
- Summary and outlook

Conclusions

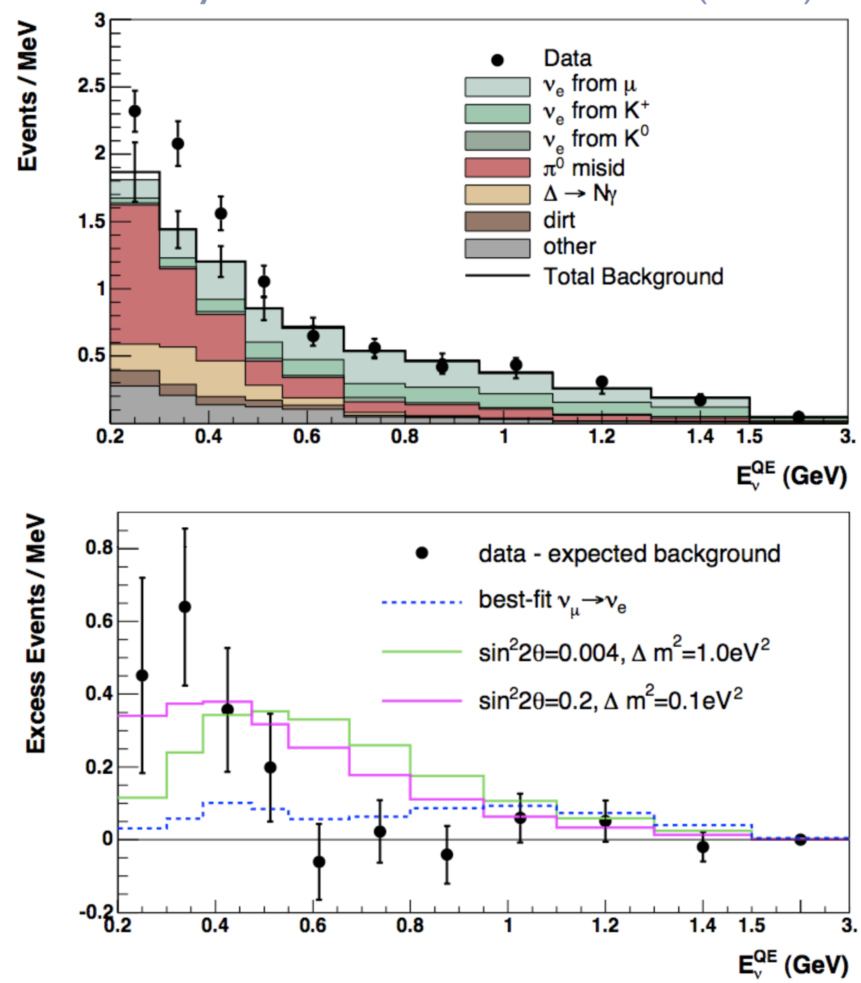
- ν_e appearance analysis exposes unexpected low energy excess mostly incompatible with oscillations
  - MicroBooNE to test details soon
- $\bar{\nu}_e$ appearance data is consistent with LSND, but will need more data to definitively discriminate
  - more data on the way, but becoming dominated by syst. errors
  - "BooNE" near detector would help immensely
- Simultaneous ν_e, $\bar{\nu}_e$ fit to CP violating model underway
- Joint MiniBooNE-SciBooNE ν_μ disappearance results sets strong limits
  - corresponding $\bar{\nu}_\mu$ analysis underway

Thanks for your attention!

BACKUP

- χ^2 probability of 93% compatible with no-osc.
- 99% compatible with best fit
  - $\sin^2(2\theta) = 10^{-3}$, $\Delta m^2 = 4$ eV^2
- Under joint analysis with LSND data and errors, 2ν osc. hyp. for LSND ruled out at 98% CL

Phys. Rev. Lett. 102: 101802 (2009)



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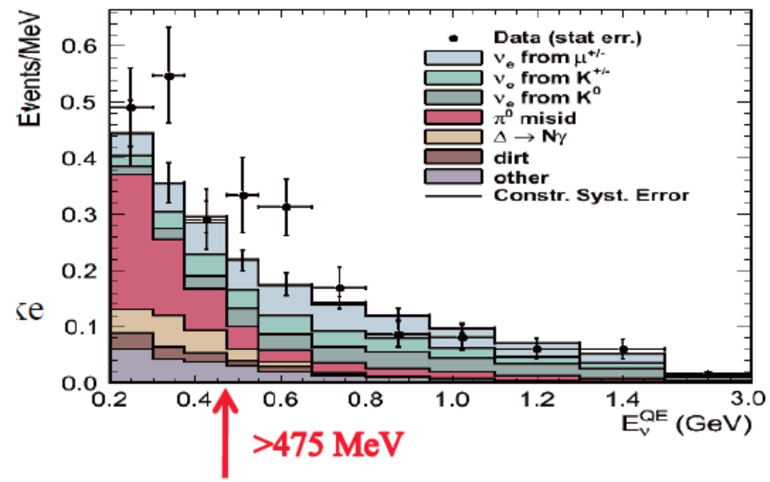
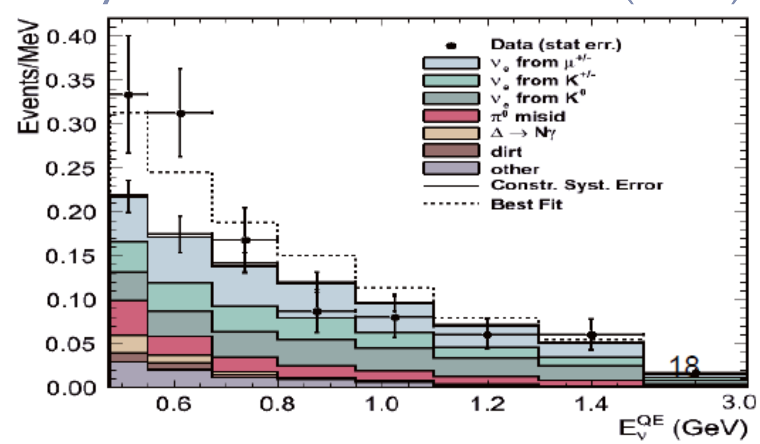


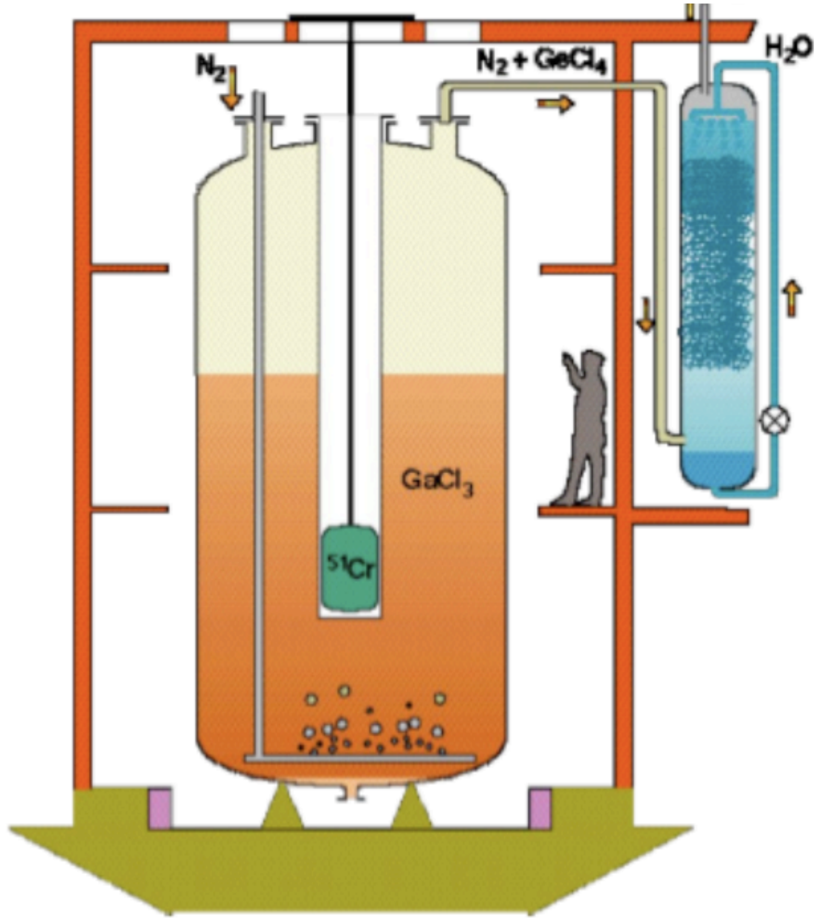
Phys. Rev. Lett. 105: 181801 (2010)



- GALLEX and SAGE radiochemical experiments combined for 4 calibration runs with MCi source
  - counted $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$
  - all 4 runs observed event deficit, with improved flux prediction $R = (obs/pred) = 0.86 \pm 0.06$ (1σ)

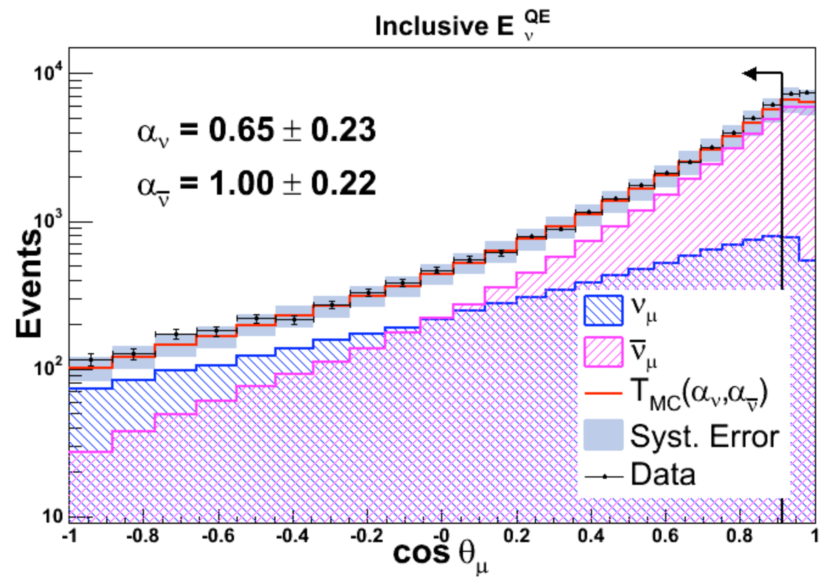
PRD **83**: 073006 (2011)

- ν_e disappearance?



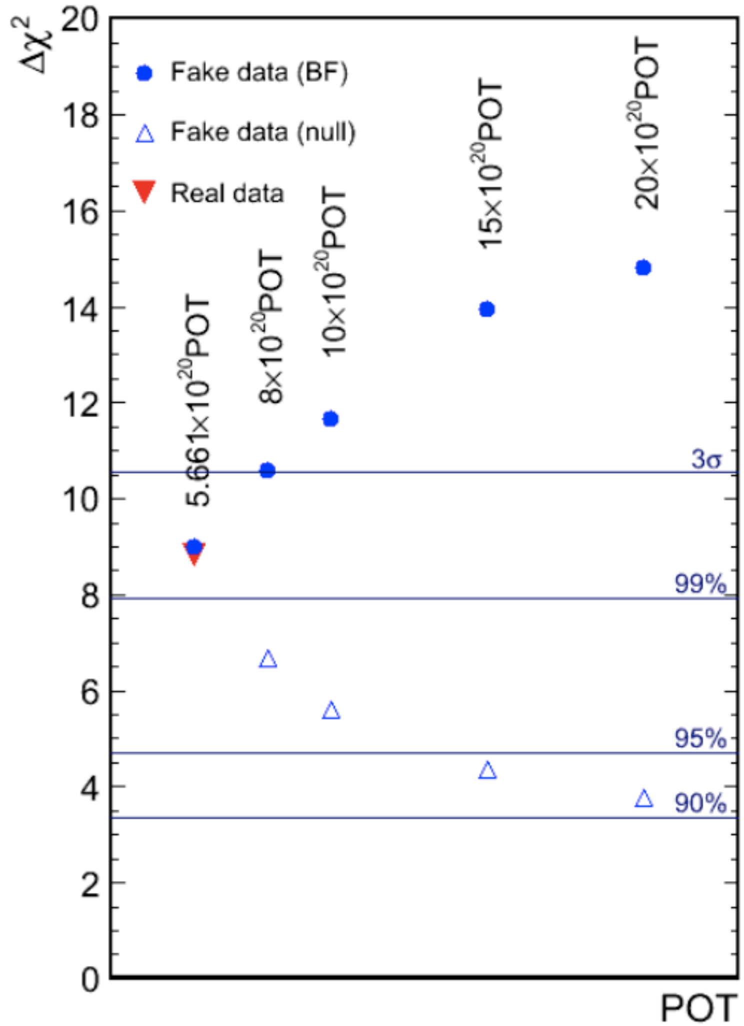
GALLEX

- Results indicate the ν_μ flux is over-predicted by ~30%
- Fit also performed in bins of reconstructed energy; consistent results indicate flux spectrum shape is well modeled



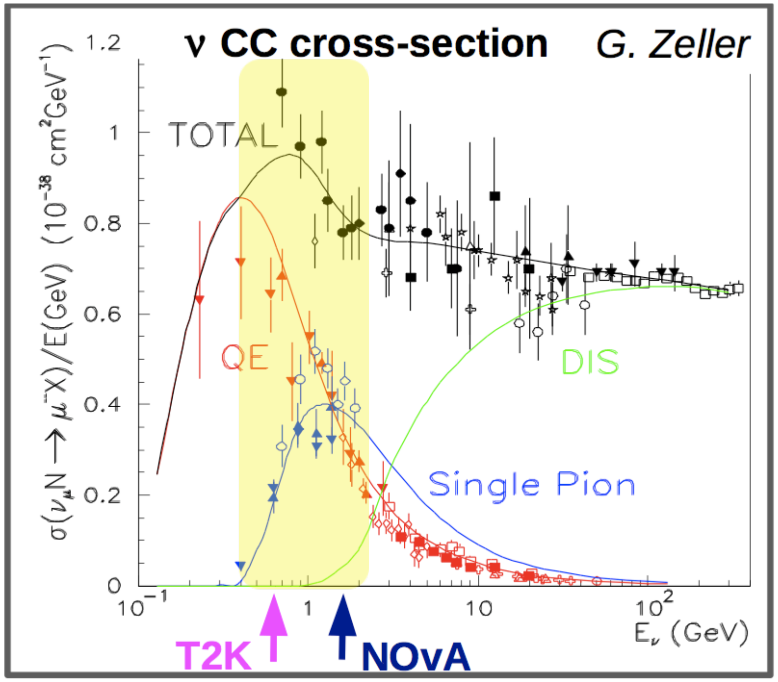
$\mathbf{E}_{\bar{\nu}}^{\mathbf{QE}}$(MeV)	α_ν	$\alpha_{\bar{\nu}}$
< 600	0.65 ± 0.22	0.98 ± 0.18
600 - 900	0.61 ± 0.20	1.05 ± 0.19
> 900	0.64 ± 0.20	1.18 ± 0.21
Inclusive	0.65 ± 0.23	1.00 ± 0.22

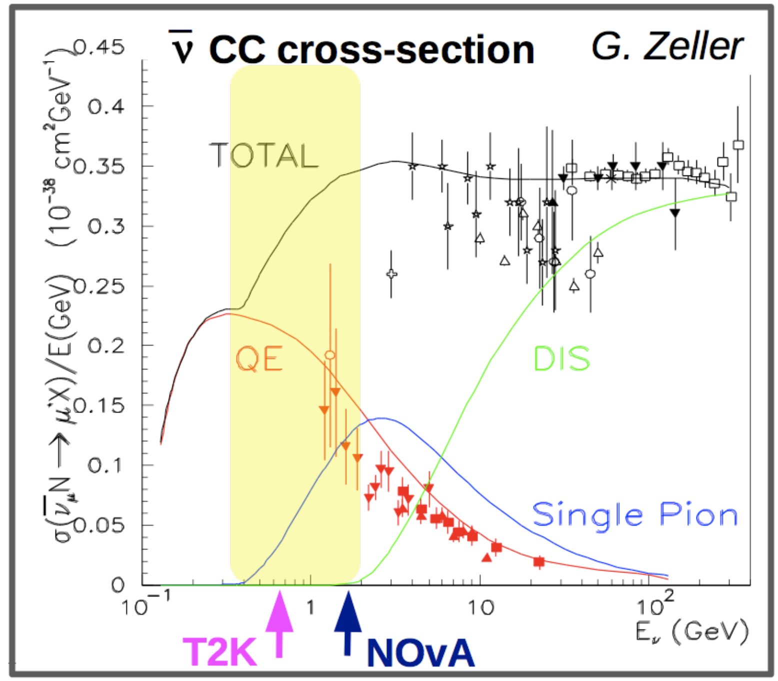
- (outdated) future $\overline{\nu}_e$ sensitivity
  - to give feel for how errors scale with POT



Physics Goals 2

Pre-MiniBooNE σ's





- Cross sections at MiniBooNE energy sparsely measured
- No sub-GeV $\bar{\nu}_\mu$ cross sections
  - Vital for future ~~CP~~ studies

- Recent results suggest these cross sections are more interesting than we thought! (later)

By requiring (μ-only/μ+e)$^{\text{data}}$ = (μ-only/μ+e)$^{\text{MC}}$ and normalization to agree in the μ+e sample we can calculate a ν_μ flux scale α_ν and a rate scale $\alpha_{\bar{\nu}}$

$$\frac{\mu}{\mu + e}^{\text{data}} = \left(\frac{\alpha_\nu \, \nu^\mu + \alpha_{\bar{\nu}} \, \bar{\nu}^\mu}{\alpha_\nu \, \nu^{\mu+e} + \alpha_{\bar{\nu}} \, \bar{\nu}^{\mu+e}} \right)^{\text{MC}}$$

Predicted neutrino content in the μ+e sample, for example

By requiring $(\mu\text{-only}/\mu+e)^{data} = (\mu\text{-only}/\mu+e)^{MC}$ and normalization to agree in the μ+e sample we can calculate a ν_μ flux scale α_ν and a rate scale $\alpha_{\bar{\nu}}$

$$\frac{\mu}{\mu+e}^{\mathrm{data}} = \left(\frac{\alpha_\nu\,\nu^\mu + \alpha_{\bar{\nu}}\,\bar{\nu}^\mu}{\alpha_\nu\,\nu^{\mu+e} + \alpha_{\bar{\nu}}\,\bar{\nu}^{\mu+e}}\right)^{\mathrm{MC}}$$

Results:

$$\alpha_\nu = 0.86 \pm 0.14$$
$$\alpha_{\bar{\nu}} = 1.09 \pm 0.23$$

PRELIMINARY